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Effects of the Mount Pinatubo Eruption on Solar Insolation: Four Case Studies

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ABSTRACT

The Southwest Technology Development Institute staff analyzed solar insolation data from four sites in the western United States recorded during the years 1990 through 1992. Analyses were performed to identify and quantify the effects on insolation caused by the eruption of Mount Pinatubo in the Philippines on June 15th and 16th 1991. Data from each of the sites were recorded by dedicated datalogging equipment. Every effort was made to prevent data acquisistion system problems (e.g., drift of the datalogger clock) from influencing the accuracy of the results.

ACKNOWLEDGMENTS

Thanks are extended to the following persons and organizations for making essential data available for use in this report:

- Ms. Vanessa Morris and the Pacific Gas and Electric Company for their contribution of the data from Carrisa Plains, California;
- Mr. Bill Marion and the National Renewable Energy Laboratory for their contribution of the data from Golden, Colorado.

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1.0 INTRODUCTION

The explosion of Mount Pinatubo in the Philippines on June 15 and 16, 1991, was the largest volcanic eruption of this century. By most accounts (1, 2, 3) Pinatubo ejected 15 to 20 million tons of ash and sulfur dioxide 23 kilometers into the stratosphere. Satellite photographs taken 21 days after the eruption show a wide belt of these contaminants encircling the globe between 25° North and 20° South latitude (1). Volcanic ash generally settles out of the atmosphere within weeks or months of an eruption. The sulfur dioxide gas mixes with moisture to become aerosol droplets of sulfuric acid that can remain in the stratosphere for several years. These aerosols scatter solar radiation in the visible wavelengths, .58 - .69 micrometers (1).

This report examines data recorded at four locations in the western United States to assess the effects of the Pinatubo eruption on solar insolation levels at these sites. The four monitoring stations that supplied the raw data for this report were:

- The Southwest Region Experiment Station in Las Cruces, New Mexico;
- The Solar Radiation Research Laboratory at the National Renewable Energy Laboratory in Golden, Colorado;
- The Solar Insolation Monitor Program station operated by the Pacific Gas and Electric Company in Carrisa Plains, California;
- The Solar Insolation monitor station at Sandia National Laboratories in Albuquerque, New Mexico.

Data from the four sites are presented below in Sections 2 through 5. Section 6 discusses the data quality assurance procedures that were followed in the preparation of this report.

2.0 LAS CRUCES, NEW MEXICO

Solar resource data have been recorded at the Southwest Region Experiment Station (SWRES) in Las Cruces, New Mexico, since the early 1980s. The site is in the Rio Grande valley in the south-central region of the state. The longitude and latitude of the location are W 106.74° and N 32.27°. The elevation is 1200 meters (3940 feet). On site is an Eppley Normal Incidence Pyrheliometer (NIP) to measure direct normal irradiance, and an Eppley Precision Spectral Pyranometer (PSP) to measure global horizontal irradiance. An Eppley shadow band and PSP have been in use since April 1991 to measure horizontal diffuse irradiance.

2.1 Recorded Insolation

Table 2-1 presents the direct normal insolation recorded in Las Cruces for the period of January 1990 through December 1992.

Table 2-1

Direct Normal Insolation for Las Cruces, New Mexico: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	194.8	155.4	97.4
February	189.0	147.2	98.7
March	204.9	207.8	168.7
April	246.8	270.3	230.6
May	267.1	294.4	162.3
June	251.3	263.8	251.1
July	204.0	164.1	227.2
August	187.2	194.0	201.1
September	177.6	160.1	214.3
October	255.4	211.3	[1]
November	190.3	174.0	166.8
December	192.4	110.5	90.7

[1] The NIP was off-line for calibration during October 1992, and data are unavailable.

Table 2-2 presents the global horizontal insolation recorded in Las Cruces during the same three-year period. These tables are presented to provide a baseline of information only. Monthly insolation totals alone cannot be used to assess the effects of the Pinatubo eruption. Ordinary weather variations may change the ratio of clear to cloudy days, giving rise to differences up to 15% in the monthly insolation totals observed from one year to another.

Table 2-2

Global Horizontal Insolation for Las Cruces, New Mexico: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	106.9	96.23	90.7
February	133.5	109.2	110.4
March	171.9	176.8	170.6
April	207.0	223.5	213.5
May	235.8	244.8	204.5
June	229.6	225.0	233.4
July	211.7	196.0	227.4
August	196.2	197.1	201.2
September	159.7	155.0	182.3
October	156.5	154.5	146.5
November	107.7	107.1	106.6
December	99.0	79.2	74.7

Figure 2-1 shows the Direct Normal Irradiance (DNI) recorded over the three-year period. Two data points are plotted for each day: the hourly average value recorded for the period from 11:00 am to 12:00 pm, and the hourly average value recorded for the period from 12:00 pm to 1:00 pm. Solar noon does not coincide with local clock time, but will fall within one of these two hourly periods throughout the year.

Figure 2-1 illustrates some of the effects of the Pinatubo eruption. The 1990 DNI data show a pattern typical of years prior to the volcano's eruption: a cycle of winter highs and summer lows. The high winter values, occurring when the sun is near perihelion, often exceeded 1000 W/m^2. The summer values, lower as a result of the increased Earth-Sun distance and increased atmospheric moisture, reached approximately 950 W/m^2. Following the Pinatubo eruption in June 1991, this cycle was disrupted. During the winter of 1991/92, DNI values did not surpass 1000 W/m^2, nor have they since the eruption.

Figure 2-2 shows the Global Horizontal Irradiance (GHI) recorded for the three-year period. Again, the two hourly records that bracket solar noon are plotted for each day.

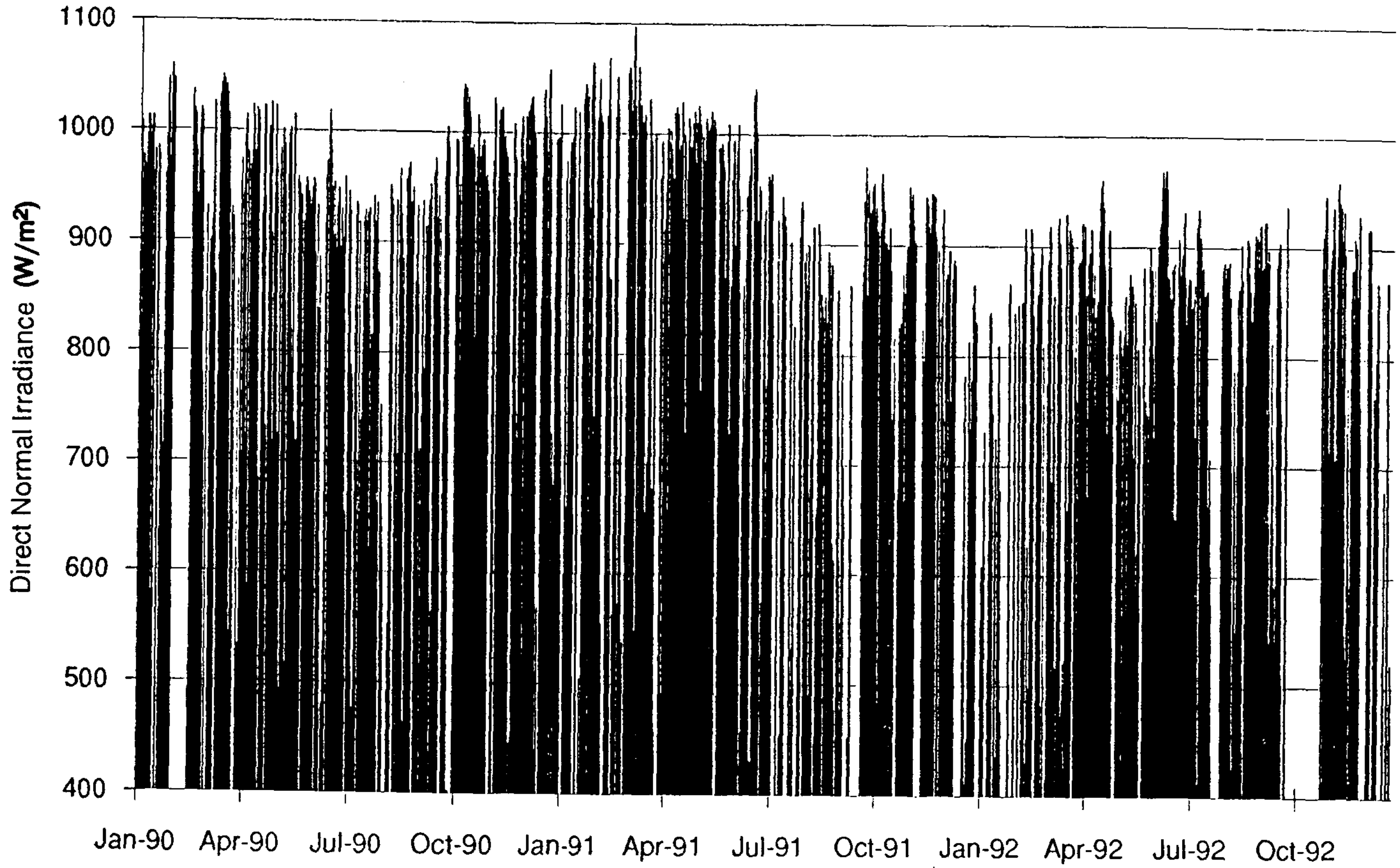

Figure 2-1. Direct Normal Irradiance -- Las Cruces, New Mexico: January 1990 through October 1992.

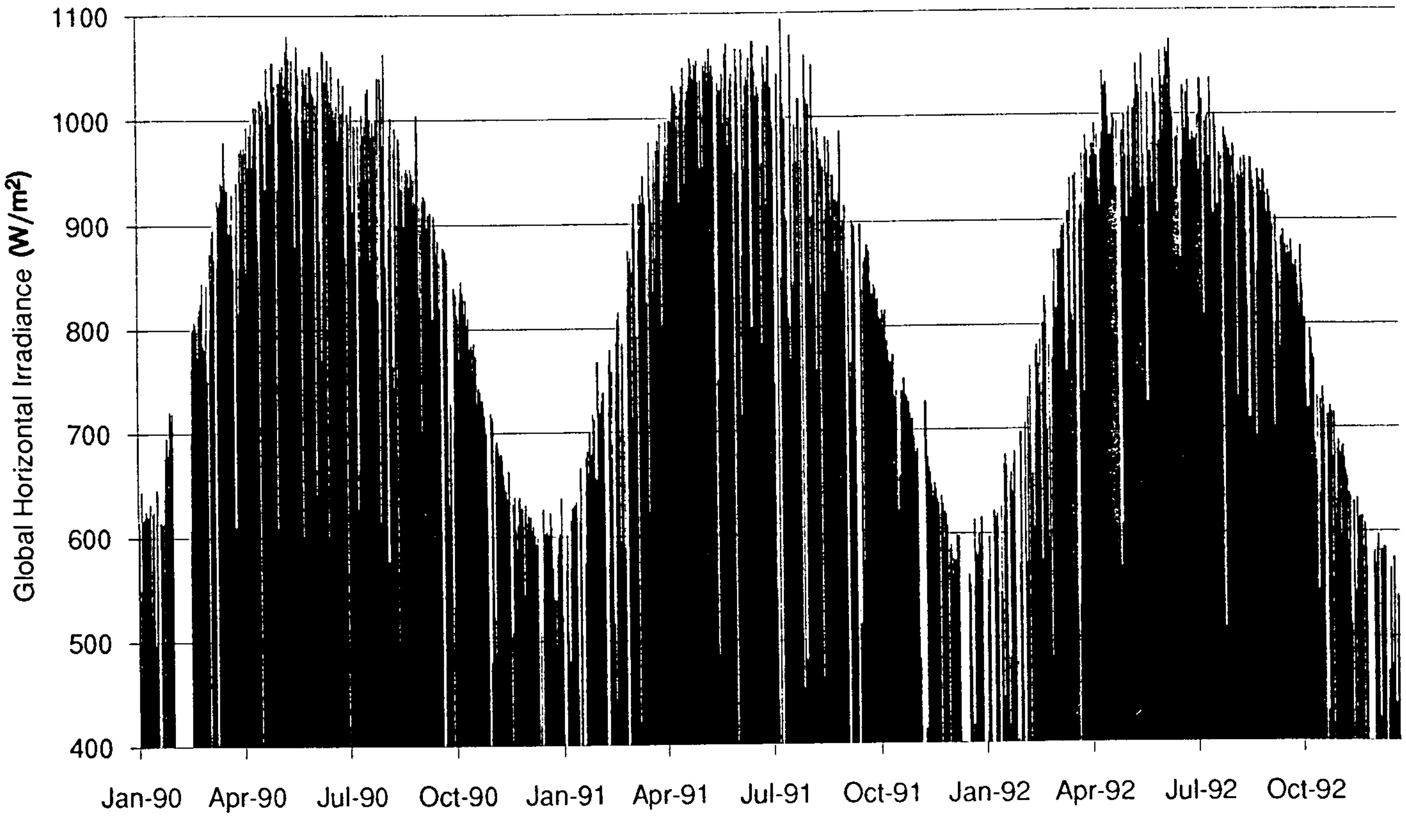

Figure 2-2. Global Horizontal Irradiance -- Las Cruces, New Mexico: January 1990 through October 1992.

The typical GHI yearly cycle shows higher values in the summer when the midday sun travels close to normal incidence to the horizontal pyranometer, and lower values in the winter when the noon sun remains lower in the southern sky. In general, the 1992 summer values are lower than those recorded in the two previous years, with some exceptions. Overall, the eruption has had less effect on the global horizontal irradiance than on the direct normal irradiance.

2.2 Effects on Direct Normal Irradiance

Figure 2-3 presents a qualitative illustration of the effects of the eruption on DNI levels recorded in Las Cruces, New Mexico. The figure shows daily quotients of 1991 vs. 1990 and 1992 vs. 1990 'clear sky' DNI values. The method used to screen for clear sky conditions extracted, for each day of the year, the single maximum DNI value observed during a 15-day period. That is, for day n, the value used was the maximum DNI observed in the period of day n-7 to day n+7. Quotients were generated by dividing the extracted value for each day of 1991 and 1992 by its corresponding 1990 value. In this way, the 1991 and 1992 data were indexed against pre-eruption (1990) conditions. Figure 2-3 shows these 'clear sky' DNI ratios determined for Las Cruces, New Mexico. While this method can not be construed as a purely quantitative comparison, it serves to illustrate the effects of the eruption on recorded DNI levels.

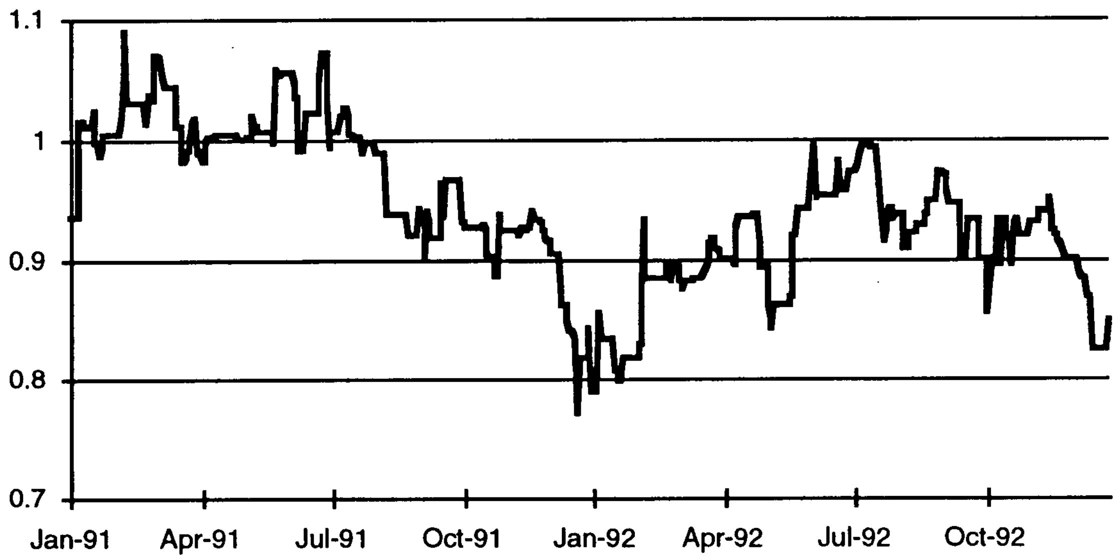

Figure 2-3. Clear Sky DNI Quotients -- Las Cruces, NM 1991/1990 and 1992/1990.

Prior to the eruption, 1991 clear sky DNI values were comparable to those recorded in 1990. The ratios for this period are approximately equal to 1.0. Following the eruption, clear sky DNI values declined. During December 1991 and January 1992, DNI values fell to approximately 80% of their 1990 levels.

During spring and summer 1992, the effects of the eruption moderated. Clear sky DNI levels recorded during June/July 1992 were within a few percent of historical (1990) levels. At year's end, however, the effects of the eruption again became more pronounced. Clear sky DNI levels dropped to less than 90% of their 1990 levels.

2.3 Typical Cloudless Days

The data were examined to select days that had been cloudless or near cloudless in each of the three years of the reporting period. Three sets of these days are presented here.

Figure 2-4 shows DNI and diffuse irradiance data recorded during individual days in February of three consecutive years: February 16, 1990; February 14, 1991; and February 14, 1992. In this case, the 1990 and 1991 data were recorded prior to the eruption. The diffuse data for 1990 and 1991 have been calculated. Figure 2-5 shows the GHI data recorded during these three days.

As shown in Figure 2-4, the DNI levels recorded during 1990 and 1991 were comparable. The 1992 levels show attenuation resulting from the eruption. Expressed on a percentage basis, the DNI was down 12% (125 W/m^2) in 1992 compared with 1990. Conversely, the 1992 diffuse data show an increase of approximately 50% (40 W/m^2) when compared with 1990.

Figure 2-6 shows the DNI and diffuse data recorded during July 17, 1990; July 17, 1991; and July 16, 1992. Figure 2-7 shows the GHI data recorded during these three days. As noted earlier, the effects of the volcano diminished during the summer months of 1992. The midday DNI values recorded during all three years were within 3%. The recorded diffuse data also show little difference over the three-year period.

Figure 2-8 shows the DNI and diffuse data recorded on December 11, 1990; December 12, 1991; and December 9, 1992. Figure 2-9 shows the GHI data recorded during these three days. Figure 2-8 illustrates the first-year and the second-year effects of the eruption. The 1991 DNI value, recorded six months after the eruption, shows a decline of 18% (125 W/m^2) when compared with 1990. In comparison, the 1992 value, recorded 18 months following the eruption, shows a decline of only 8% (79 W/m^2) compared with 1990 levels.

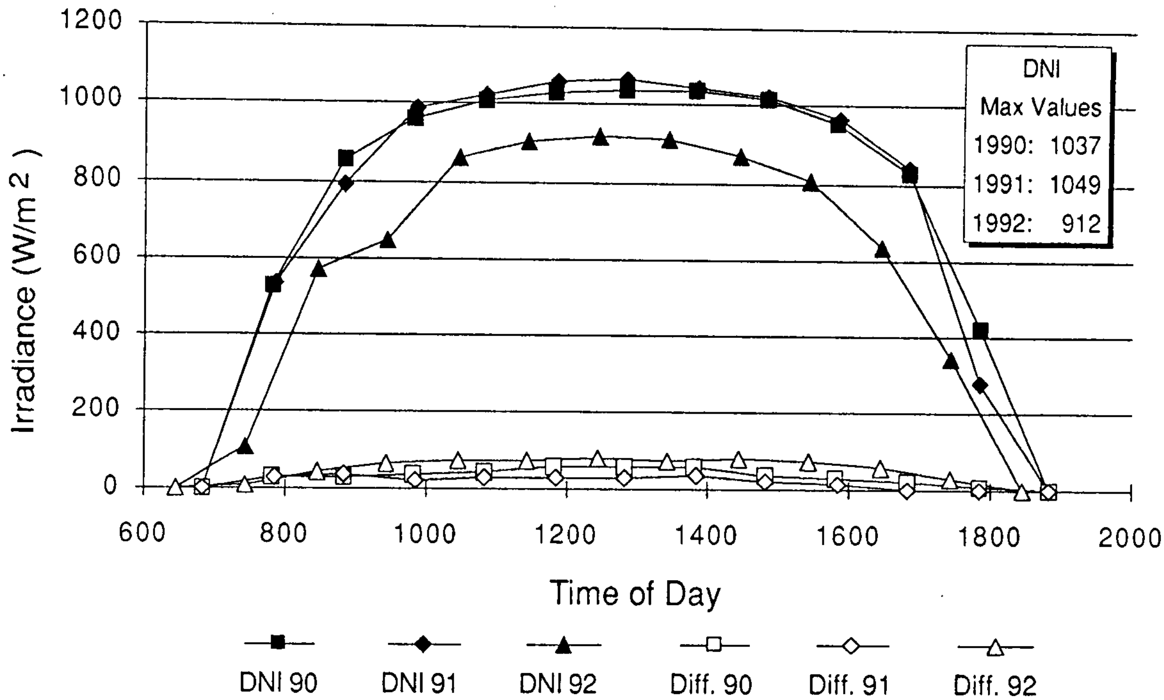

Figure 2-4. Direct Normal and Diffuse Irradiance -- Las Cruces, New Mexico 2/16/90, 2/14/91, 2/14/92.

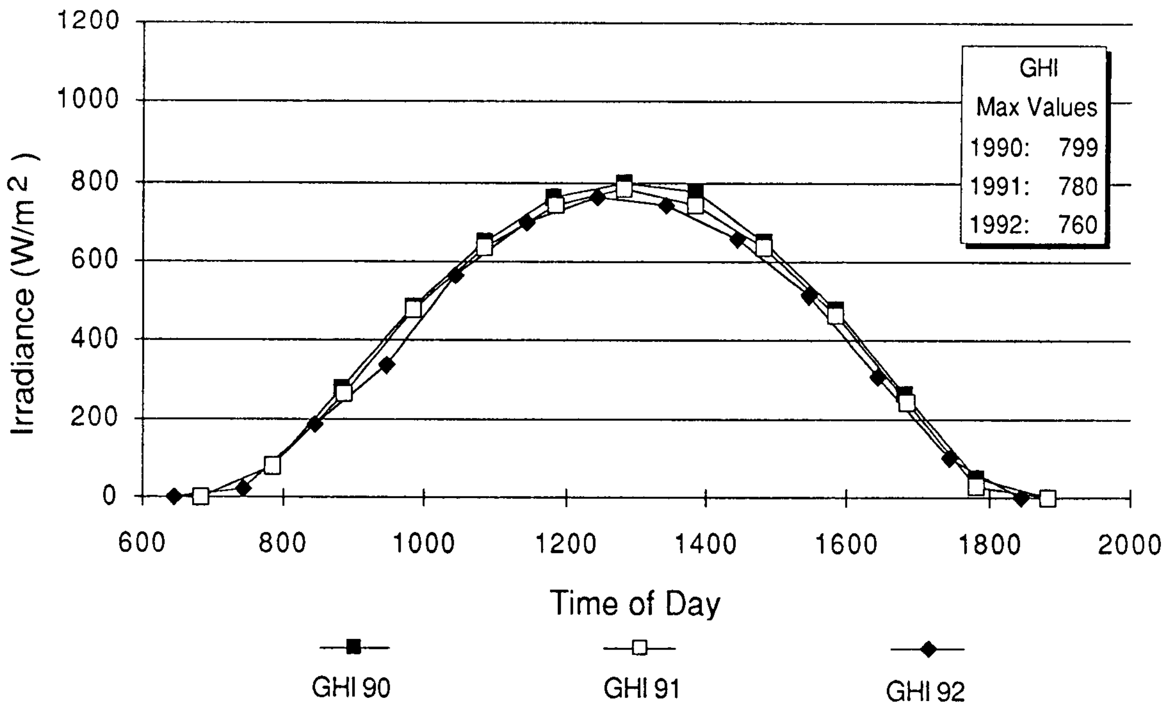

Figure 2-5. Global Horizontal Irradiance -- Las Cruces, New Mexico 2/16/90, 2/14/91, 2/14/92.

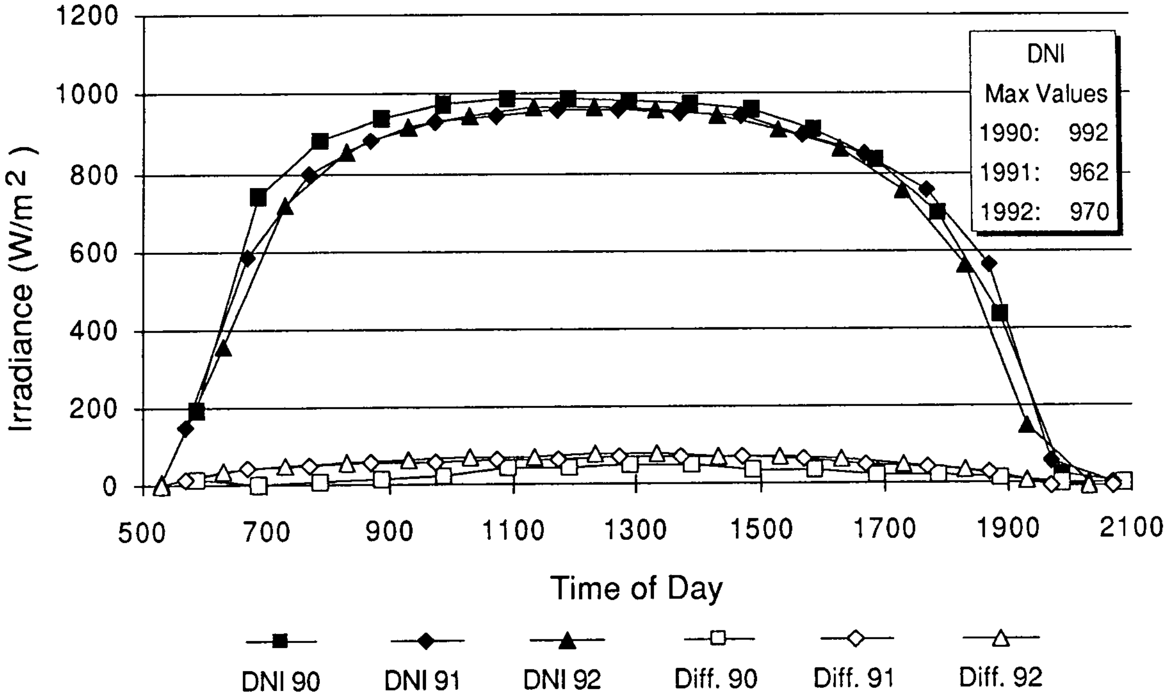

Figure 2-6. Direct Normal and Diffuse Irradiance -- Las Cruces, New Mexico 7/17/90, 7/17/91, 7/16/92.

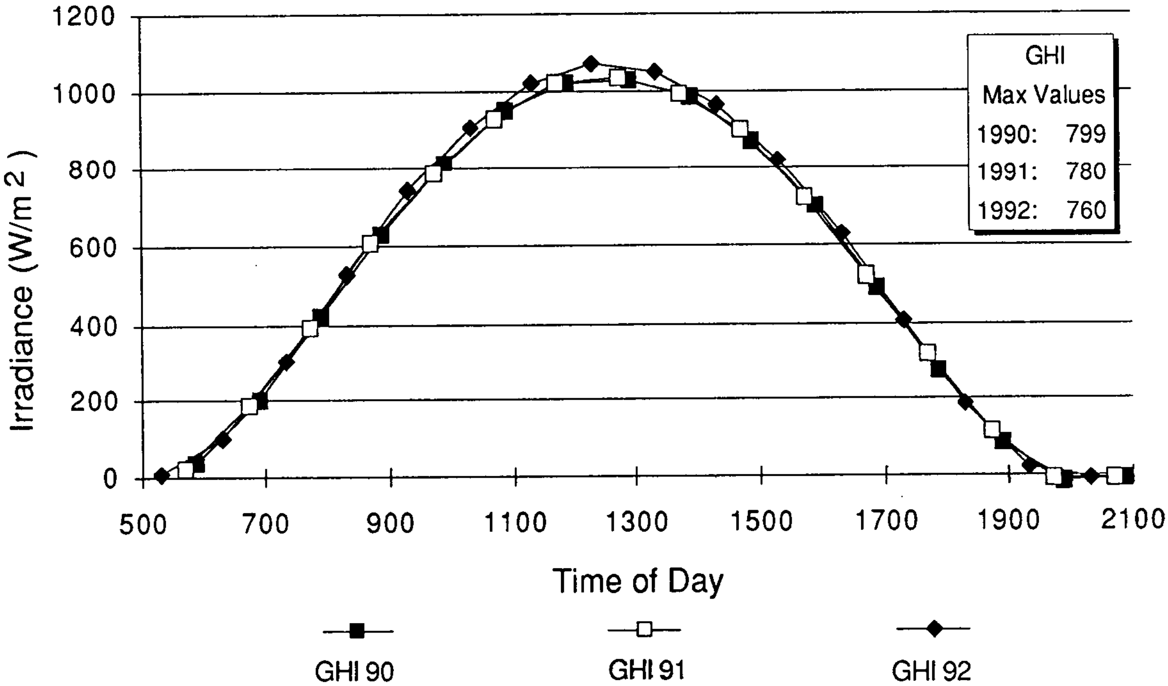

Figure 2-7. Global Horizontal Irradiance -- Las Cruces, New Mexico 7/17/90, 7/17/91, 7/16/92.

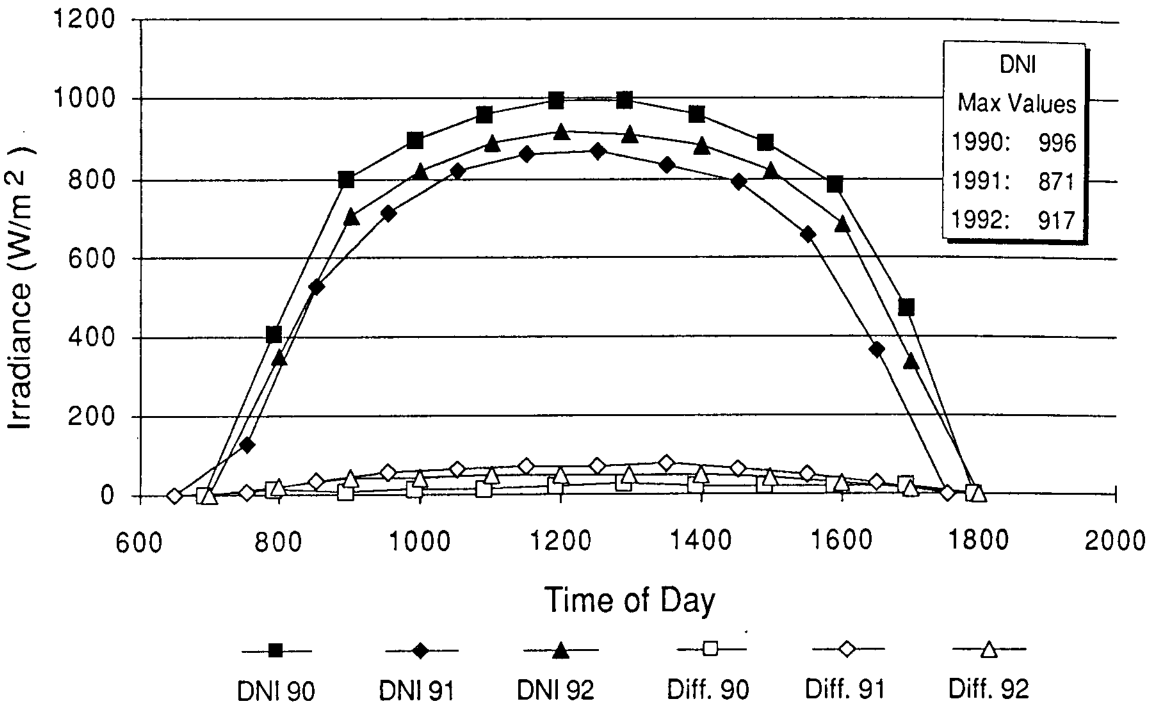

Figure 2-8. Direct Normal and Diffuse Irradiance -- Las Cruces, New Mexico 12/11/90, 12/12/91, 12/9/92.

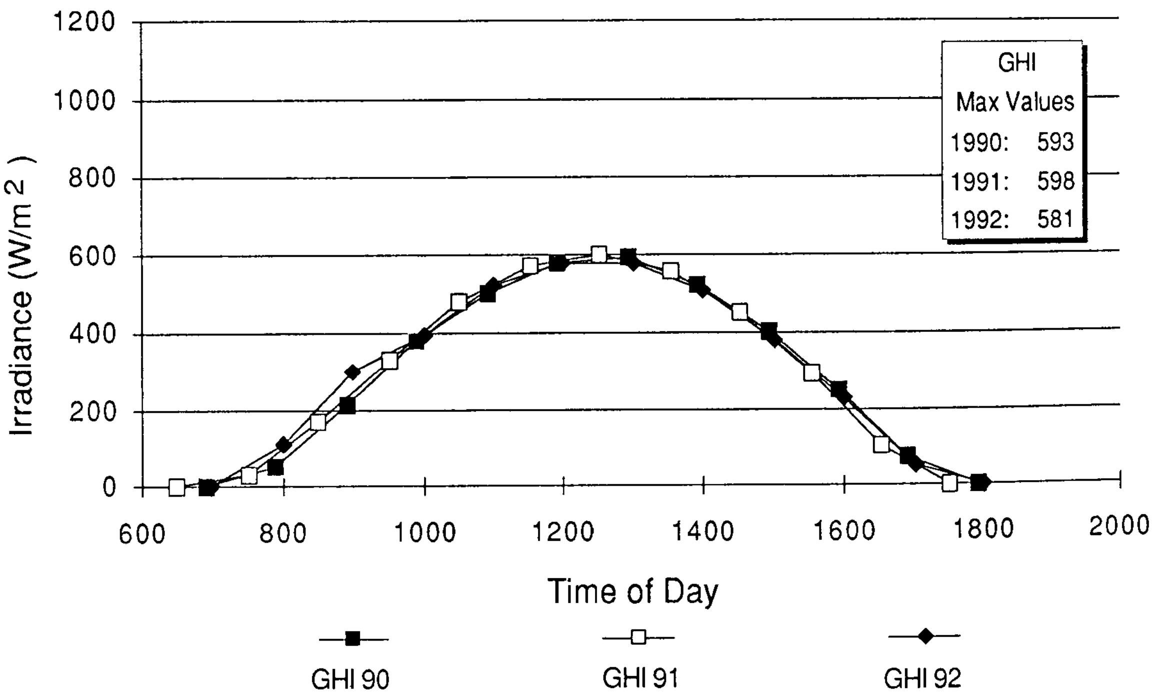

Figure 2-9. Global Horizontal Irradiance -- Las Cruces, New Mexico 12/11/90, 12/12/91, 12/9/92.

3.0 GOLDEN, COLORADO

The National Renewable Energy Laboratory (NREL) has been collecting solar and meteorological data at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado, since 1981. The site was originally located at the base of South Table Mountain but was moved to the top of the mountain in 1983. The longitude and latitude of the location are W 105.18° and N 39.74°. The elevation is 1829 meters (6000 feet). Approximately 25 solar and meteorological instruments are in use at the site. This report makes use of data from three of these instruments: an Eppley Normal Incidence Pyrheliometer (NIP) to measure direct normal irradiance; an Eppley Precision Spectral Pyranometer (PSP) to measure global horizontal irradiance; and an Eppley shadow band and PSP to measure horizontal diffuse irradiance.

3.1 Recorded Insolation

Table 3-1 presents the direct normal insolation recorded in Golden for the period of January 1990 through November 1992. In this reporting period, 35 events were experienced during which data from the NIP were unavailable. The longest of these was the period of March 28, 1992 through April 27, 1992 when the NIP was off-line for recalibration.

Table 3-1

Direct Normal Insolation for Golden, Colorado: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	172.0	149.4	132.5
February	135.1	141.0	110.8
March	131.9	194.4	107.1
April	119.5	129.5	[1]
May	180.2	166.7	131.0
June	249.0	181.0	164.2
July	160.3	208.0	172.6
August	192.0	166.0	139.0
September	186.4	174.1	196.8
October	191.8	171.1	134.0
November	142.9	119.0	91.3
December	157.2	123.4	-

[1] The NIP was off-line for calibration during most of April 1992, and data are unavailable.

Table 3-2 presents the global horizontal insolation recorded in Golden during the same three-year period. As stated earlier, tables of monthly insolation totals alone cannot be used to assess the effects of the Pinatubo eruption.

Table 3-2
Global Horizontal Insolation for Golden, Colorado: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	82.2	81.0	80.6
February	89.2	91.9	96.2
March	122.8	148.3	125.3
April	135.4	149.6	275.3
May	187.8	185.1	140.0
June	223.4	188.8	202.5
July	170.4	193.1	152.7
August	174.7	164.4	164.2
September	145.3	146.7	169.4
October	119.7	119.0	111.2
November	78.1	77.4	74.1
December	74.2	70.5	-

Figure 3-1 shows the Direct Normal Irradiance (DNI) recorded over the period of January 1990 through November 1992. Two data points are plotted for each day: the hourly average value recorded for the period from 11:00 am to 12:00 pm, and the hourly average value recorded for the period from 12:00 pm to 1:00 pm. Figure 3-2 shows the Global Horizontal Irradiance (GHI) recorded for the three-year period. Again, the two hourly records that bracket solar noon are plotted for each day.

The DNI data for Golden, Colorado, are similar to those recorded in Las Cruces, New Mexico (presented in Section 1). During 1990, a yearly cycle of winter highs and summer lows was observed. As in Las Cruces, winter highs exceeding 1000 W/m^2 were often recorded. During the summer of 1990, midday DNI levels decreased, reaching approximately 950 W/m^2. Following the Pinatubo eruption in June 1991, this cycle was altered. DNI values remained near 900 W/m^2 during the winter of 1991/92 and during the last quarter of 1992.

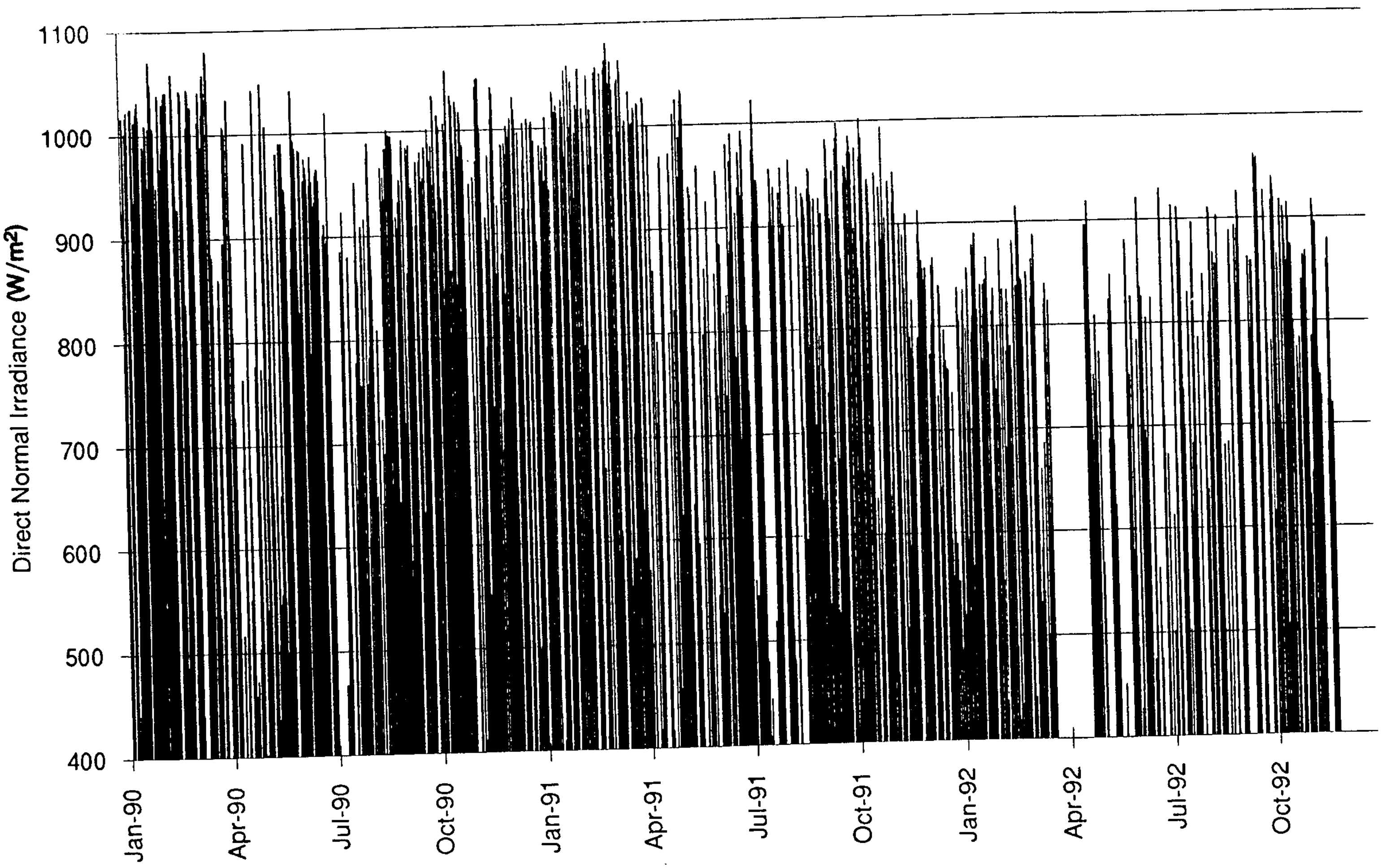

Figure 3-1. Direct Normal Irradiance -- Golden, Colorado: January 1990 through November 1992.

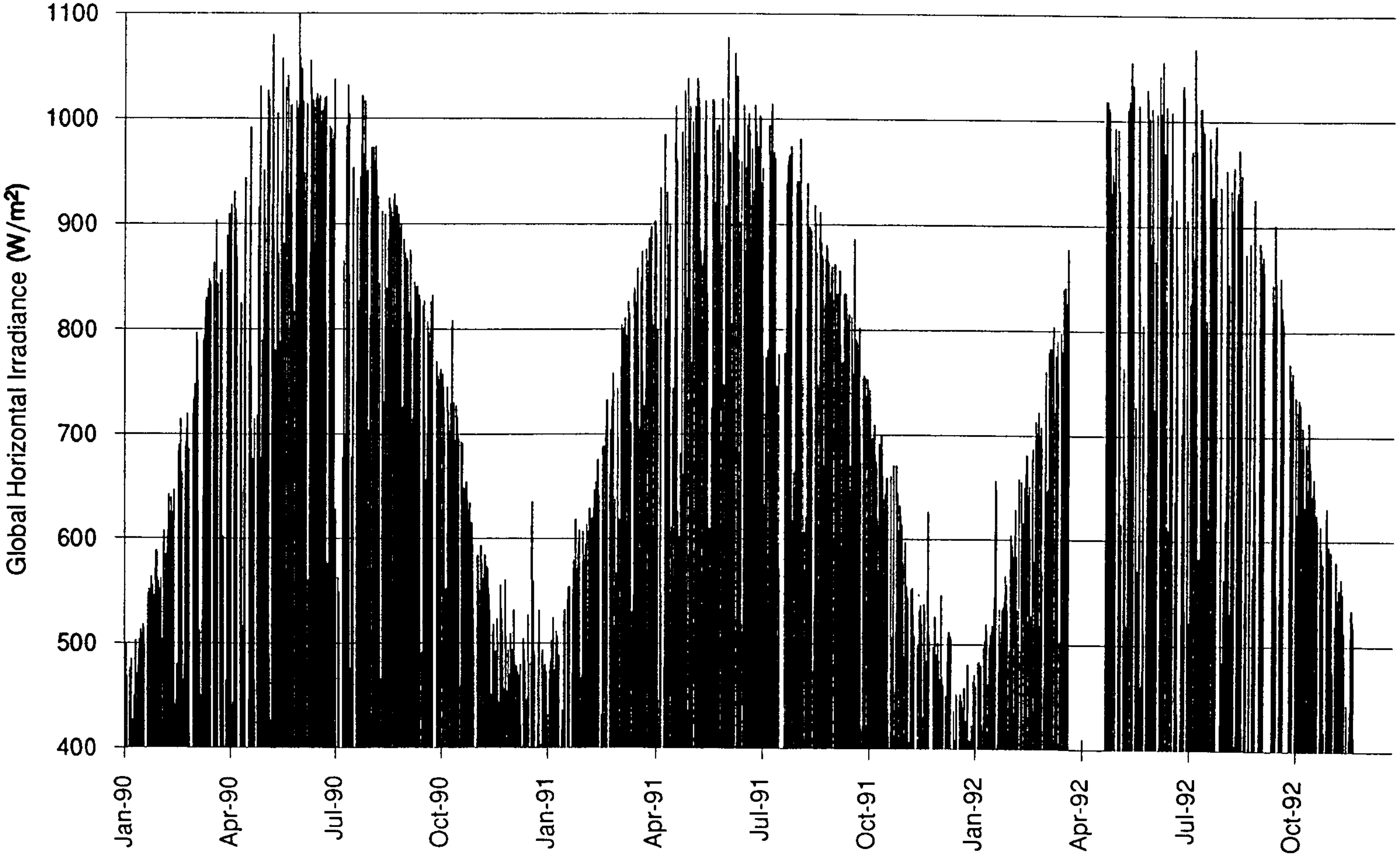

Figure 3-2. Global Horizontal Irradiance -- Golden, Colorado: January 1990 through November 1992.

3.2 Effects on Direct Normal Irradiance

Figure 3-3 presents a qualitative illustration of the effects of the Pinatubo eruption on DNI levels recorded in Golden, Colorado. The figure shows daily quotients of 1991 vs. 1990 and 1992 vs. 1990 'clear sky' DNI values. As outlined in the previous section, the method used to screen for clear sky conditions extracted, for each day of the year, the single maximum DNI value observed during a 15-day period. That is, for day n, the value used was the maximum DNI observed in the period of day n-7 to day n+7. Quotients were generated by dividing the extracted value for each day of 1991 and 1992 by its corresponding 1990 value. In this way, the 1991 and 1992 data were indexed against pre-eruption (1990) conditions.

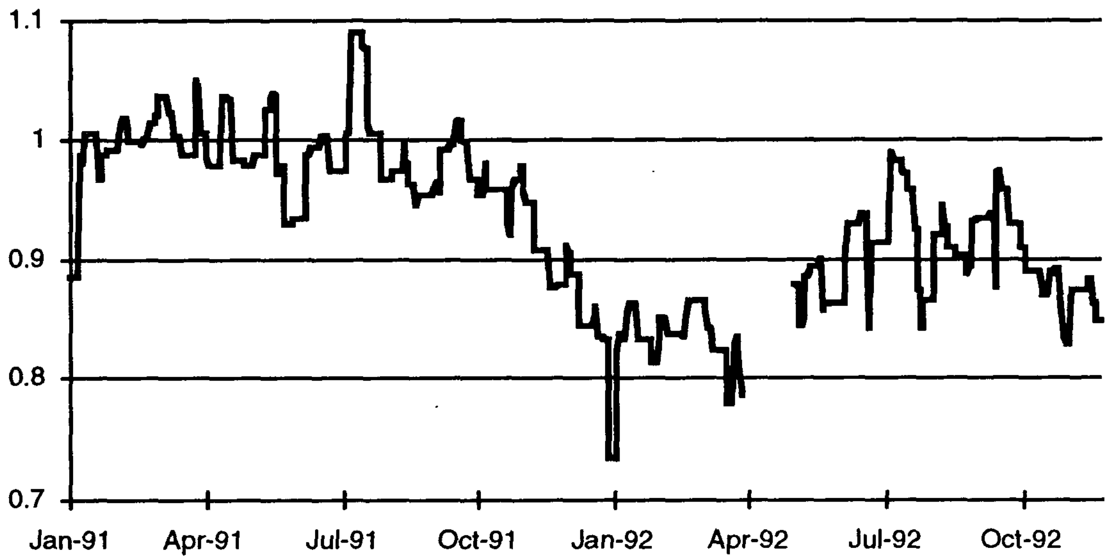

Figure 3-3. Clear Sky DNI Quotients -- Golden, CO 1991/1990 and 1992/1990.

Prior to the eruption, 1991 clear sky DNI values were unchanged from what they had been in 1990. Ratios of approximately 1.0 were determined for the first six months of 1991. Following the eruption, clear sky DNI values declined steadily. Minimum levels were recorded in January 1992, when DNI values fell to approximately 85% of their 1990 levels. As observed elsewhere, the effects of the eruption abated during the summer months of 1992. Clear sky DNI levels returned to within a few percent of their

1990 levels. At year's end, however, the effects of the eruption were again evident. At that time, clear sky DNI levels dropped to less than 90% of their recorded 1990 levels.

3.3 Typical Cloudless Days

The data were examined to select days that had been cloudless or near cloudless in each of the three years. Golden had fewer days that were cloudless in consecutive years than did the other sites evaluated in this report. Two sets of these days are presented here.

Figure 3-4 shows DNI and diffuse data recorded during individual days in either February or March of three consecutive years: March 2, 1990; March 7, 1991; and February 28, 1992. Figure 3-5 shows the GHI data recorded during these three days.

As shown in Figure 3-4, the DNI values for 1990 and the pre-eruption period of 1991 were comparable. In 1992, the recorded DNI data show attenuation resulting from the eruption. Expressed on a percentage basis, the DNI was down 12% (128 W/m^2) in 1992 compared with 1990. The midday 1992 diffuse data show an increase of approximately 50 W/m^2 compared with 1990.

Figure 3-6 shows the DNI and diffuse data recorded during October 21, 1990; October 21, 1991; and October 10, 1992. Figure 3-7 shows the GHI data recorded during these three days. Figure 3-6 shows the first-year and the second-year effects of the eruption. The peak 1991 DNI value (943 W/m^2), recorded four months after the eruption, is 9% lower than 1990 value (1034 W/m^2). The 1992 value (917 W/m^2), recorded 16 months following the eruption, shows a decline of 11% compared to 1990 levels.

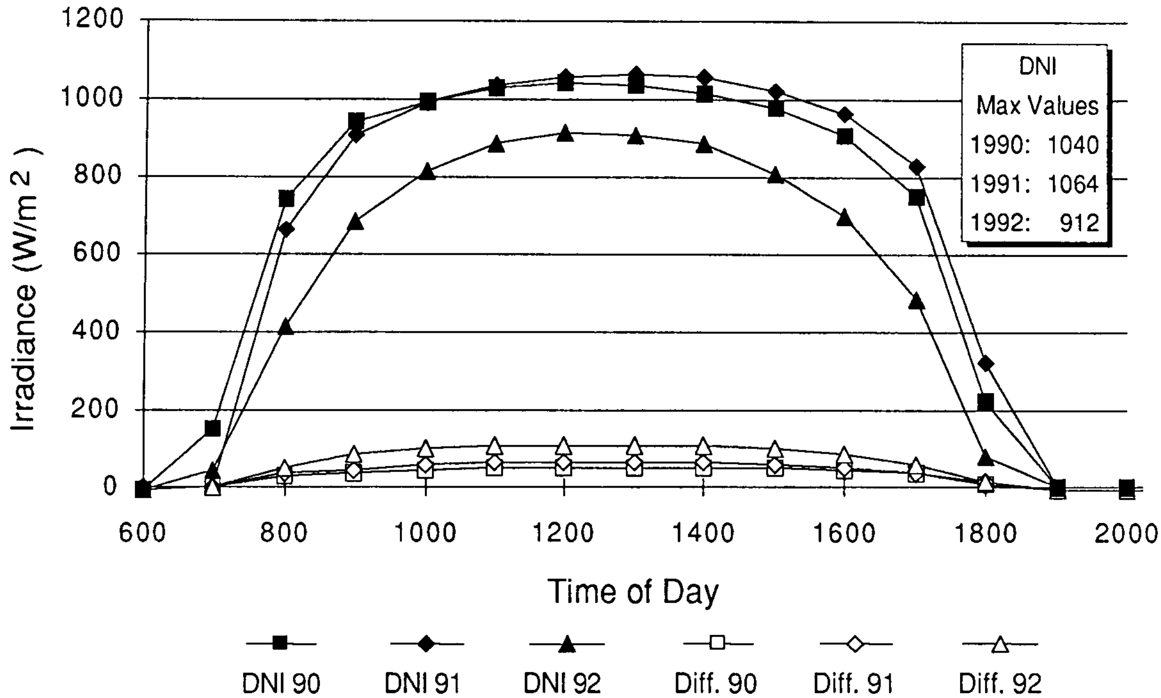

Figure 3-4. Direct Normal and Diffuse Irradiance -- Golden, Colorado
3/2/90, 3/7/91, 2/28/92.

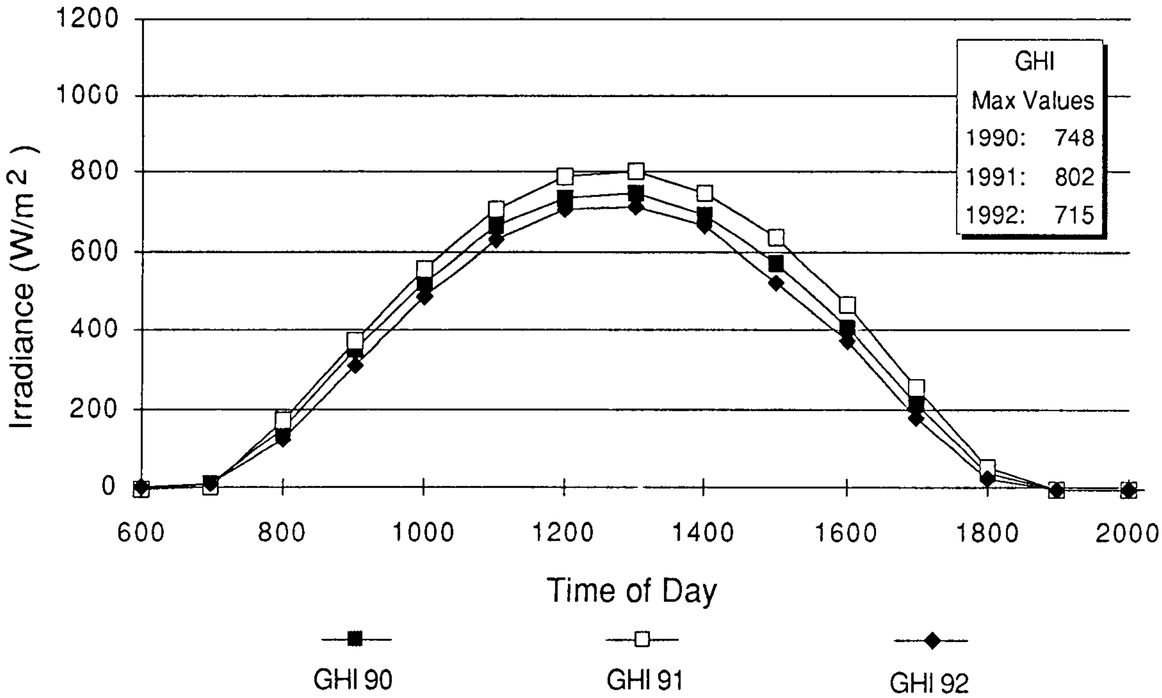

Figure 3-5. Global Horizontal Irradiance -- Golden, Colorado
3/2/90, 3/7/91, 2/28/92.

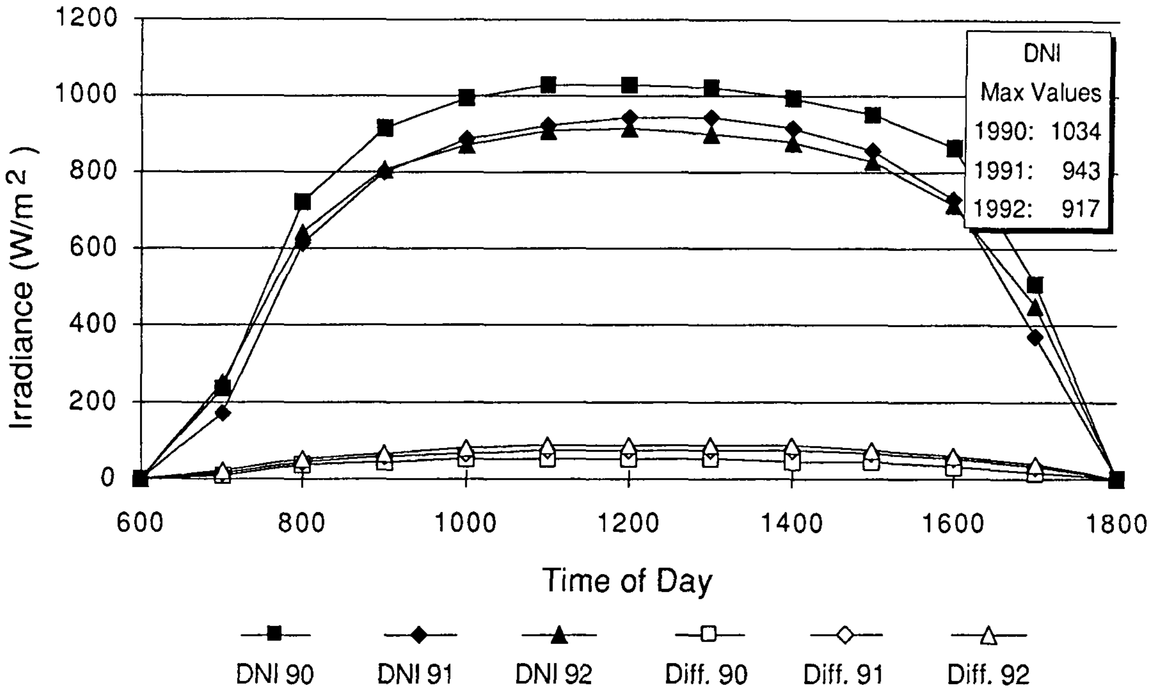

Figure 3-6. Direct Normal and Diffuse Irradiance -- Golden, Colorado 10/21/90, 10/21/91, 10/10/92.

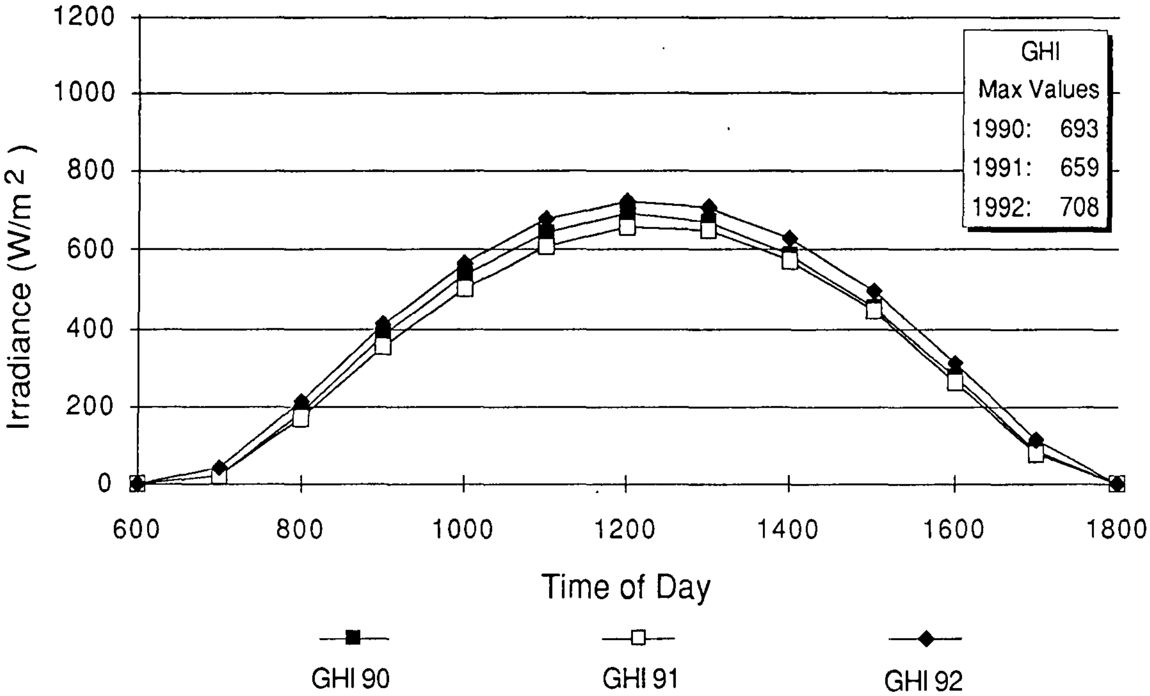

Figure 3-7. Global Horizontal Irradiance -- Golden, Colorado 10/21/90, 10/21/91, 10/10/92.

4.0 CARRISA PLAINS, CALIFORNIA

Pacific Gas and Electric Company (PG&E) has conducted weather monitoring under its Solar Insolation Monitoring Project (SIMP) at 14 different sites throughout its service territory in northern and central California since 1984. For this report, PG&E made available data recorded at Carrisa Plains, California. The site is in the California valley in the central region of the state. The longitude and latitude of the location are W 120.05° and N 35.35°. The elevation is 609 meters (2000 feet). On site is an Eppley Normal Incidence Pyrheliometer (NIP) to measure direct normal irradiance, and an Eppley Precision Spectral Pyranometer (PSP) to measure global horizontal irradiance.

4.1 Recorded Insolation

Table 4-1 presents the direct normal insolation recorded in Carrisa Plains for the period of January 1990 through April 1992.

Table 4-1

Direct Normal Insolation for Carrisa Plains, California: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	153.9	138.6	130.9
February	148.0	153.4	92.0
March	189.8	140.4	81.4
April	208.5	221.8	190.5
May	271.4	276.2	-
June	318.2	281.2	-
July	320.1	304.9	-
August	287.8	268.6	-
September	248.4	233.0	-
October	244.7	206.1	-
November	192.0	168.7	-
December	183.3	118.3	-

Table 4-2 presents the global horizontal insolation recorded in Carrisa Plains during the same three-year period.

Table 4-2

Global Horizontal Insolation for Carrisa Plains, California: 1990 - 1992

Month	1990 (kWh/m^2)	1991 (kWh/m^2)	1992 (kWh/m^2)
January	95.5	91.6	97.3
February	114.7	110.6	98.4
March	169.1	137.8	126.5
April	198.9	206.3	206.0
May	243.0	247.3	-
June	261.9	248.5	-
July	262.8	253.9	-
August	234.4	222.7	-
September	187.2	185.3	-
October	157.4	145.8	-
November	109.8	110.1	-
December	95.1	84.5	-

Figure 4-1 shows the Direct Normal Irradiance (DNI) recorded over the three-year period. Two data points are plotted for each day: the half-hourly average value recorded for the period from 11:30 am to 12:00 pm and the half-hourly average value recorded for the period from 12:00 pm to 12:30 pm.

The effects of the Pinatubo eruption are seen in Figure 4-1. During the period of January 1990 through June 1991, the clear sky DNI often reached levels of 1000 W/m^2. Following the Pinatubo eruption in June 1991, a steady decline in the clear sky DNI values was recorded. Midday DNI levels declined to approximately 900 W/m^2 or less. After the eruption, values in excess of 1000 W/m^2 were no longer observed.

Figure 4-2 shows the Global Horizontal Irradiance (GHI) recorded for the three-year period. As with other sites, effects of the volcano on the global irradiance are less discernible than effects on the direct normal component.

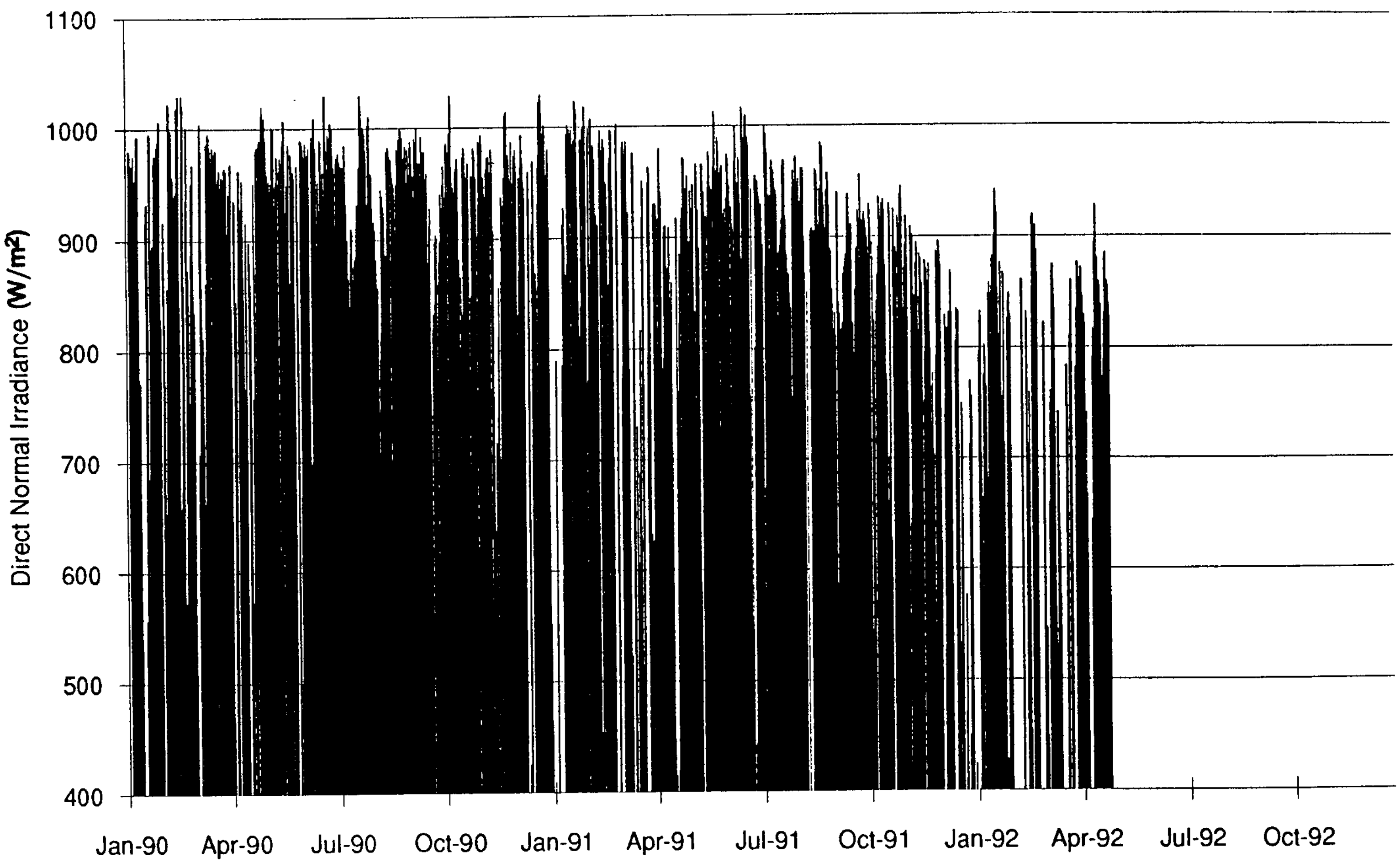

Figure 4-1. Direct Normal Irradiance -- Carrisa Plains, California: January 1990 through October 1992.

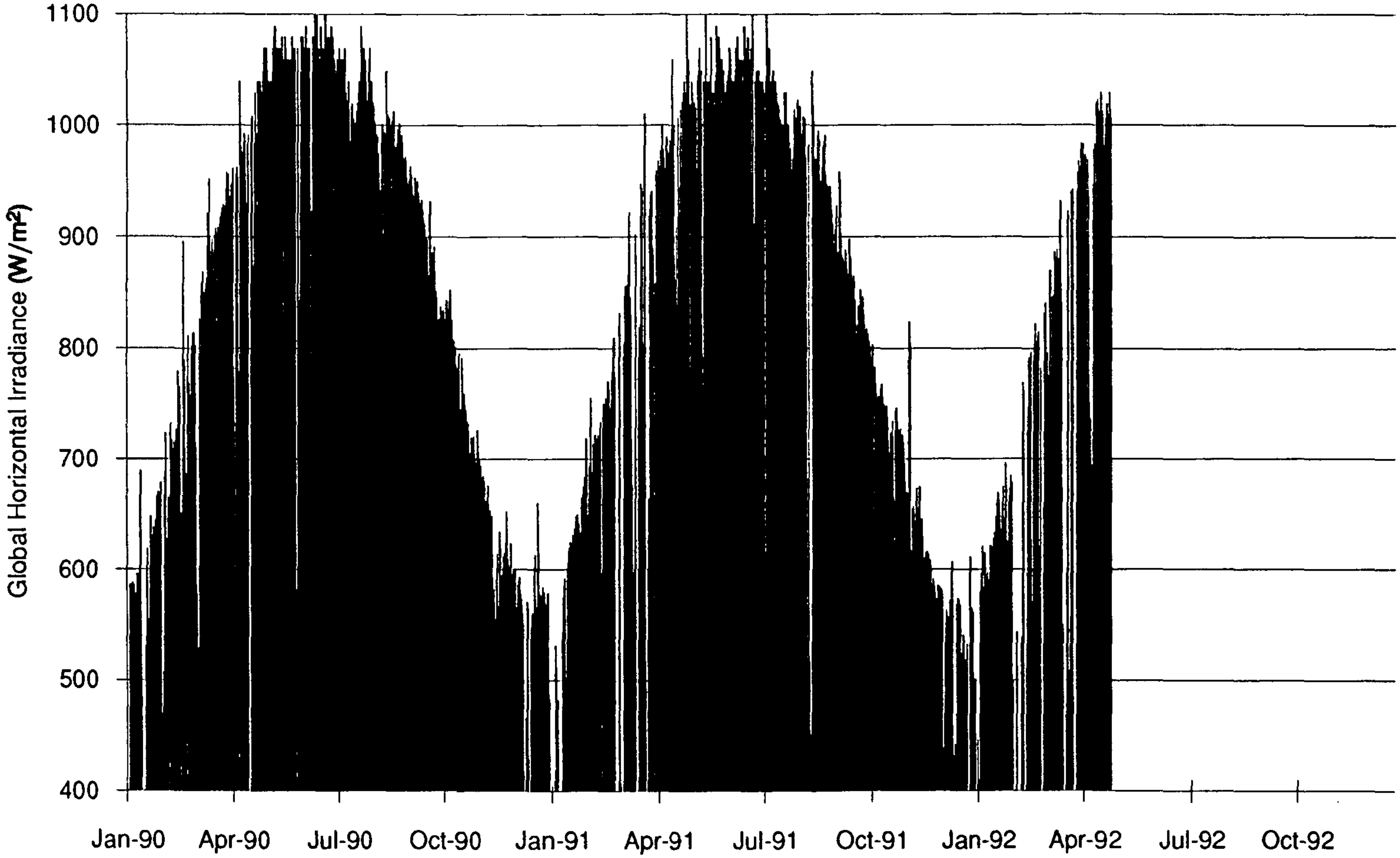

Figure 4-2. Global Horizontal Irradiance -- Carrisa Plains, California: January 1990 through October 1992.

4.2 Effects on Direct Normal Irradiance

Figure 4-3 presents a qualitative illustration of the effects of the Pinatubo eruption on DNI levels recorded in Carrisa Plains, CA. The figure shows daily quotients of 1991 vs. 1990 and 1992, vs. 1990 'clear sky' DNI values. Data for 1992 are available only through the end of April. As outlined in the previous section, the method used to screen for clear sky conditions was to extract, for each day of the year, the single maximum DNI value observed during a 15-day period. That is, for day n, the value used was the maximum DNI observed in the period of day n-7 to day n+7. Quotients were generated by dividing the extracted value for each day of 1991 and 1992 by its corresponding 1990 value. In this way, the 1991 and 1992 data were indexed against pre-eruption (1990) conditions.

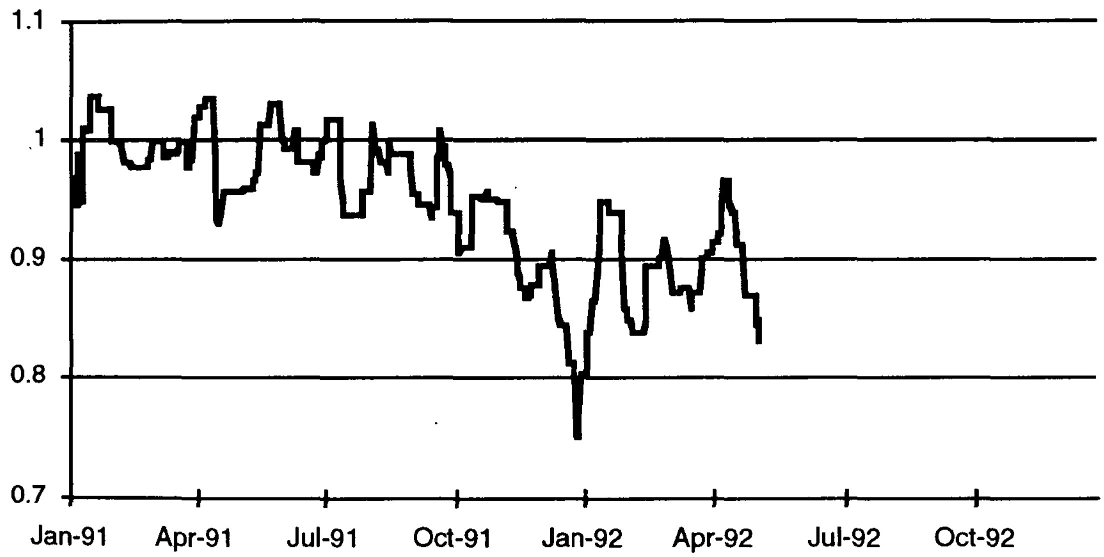

Figure 4-3. Clear Sky DNI Quotients -- Carrisa Plains, CA 1991/1990 and 1992/1990.

For the months prior to the eruption, 1991 clear sky DNI values were similar to what they had been in 1990. Ratios remained approximately equal to 1.0. Following the eruption, clear sky DNI values declined. During December 1991 and January 1992, DNI values fell to approximately 80% of their 1990 levels. During spring 1992, the effects of the eruption moderated, as observed at other sites. Data are not available after April 1992.

4.3 Typical Cloudless Days

The data were examined to select days that had been cloudless or near cloudless in each of the three years of the reporting period. Three sets of these days are presented here.

Figure 4-4 shows DNI and diffuse data recorded during individual days in January of three consecutive years: January 21, 1990; January 23, 1991; and January 23, 1992. The 1990 and 1991 data were recorded prior to the eruption. The diffuse data for all three years have been calculated. Figure 4-5 shows the GHI data recorded during these three days.

As shown in Figure 4-4, the DNI levels recorded during 1990 and the pre-eruption period of 1991 were roughly comparable. The 1992 levels have been attenuated by the eruption. Expressed on a percentage basis, the DNI was down 5% (49 W/m^2) in 1992 compared with 1990, and down 10% (100 W/m^2) when compared with 1991. Conversely, the midday 1992 diffuse data show an increase of approximately 50 W/m^2 compared with 1990, and 70 W/m^2 compared with 1991.

Figure 4-6 shows the DNI and diffuse data recorded during December 8, 1990, and December 4, 1991. Figure 4-7 shows the GHI data recorded during these two days. Data for this day in 1992 are not available. In this case, the 1991 data were recorded six months after the eruption. The DNI values recorded at 12:00 were 993 and 897 W/m^2 in 1990 and 1991, respectively. The 1991 diffuse irradiance increased by 50 W/m^2 compared with 1990. Interestingly, despite these changes, the net result left the GHI values for the two years virtually identical.

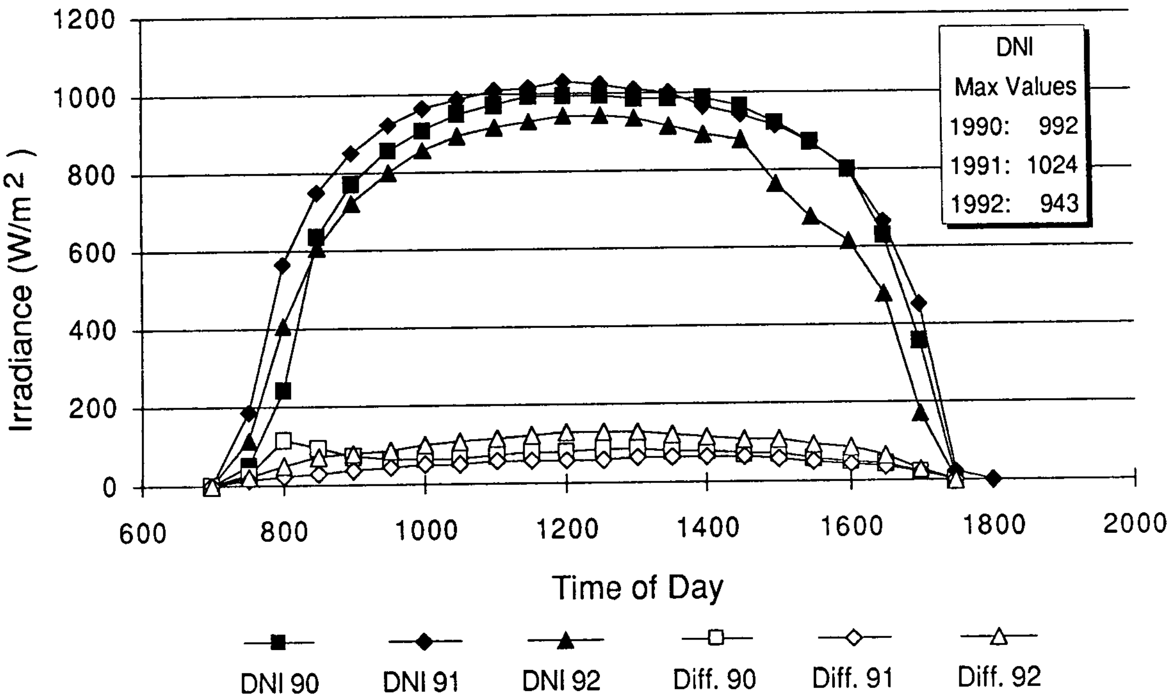

Figure 4-4. Direct Normal and Diffuse Irradiance -- Carrisa Plains, California 1/21/90, 1/23/91, 1/23/92.

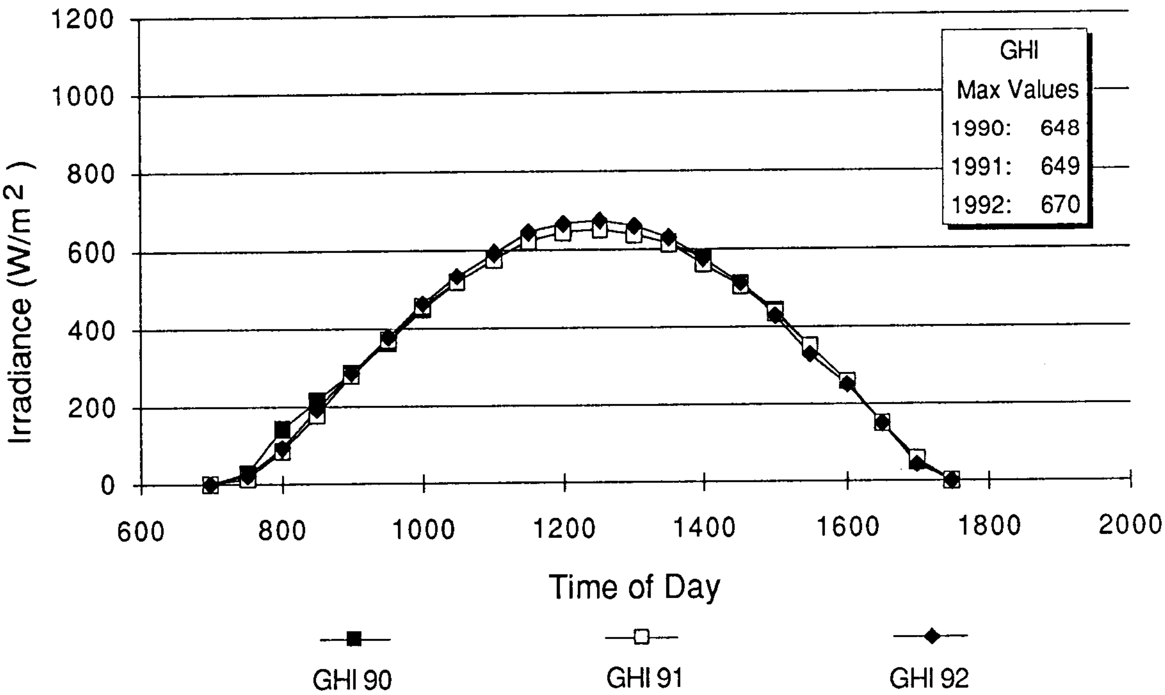

Figure 4-5. Global Horizontal Irradiance -- Carrisa Plains, California 1/21/90, 1/23/91, 1/23/92.

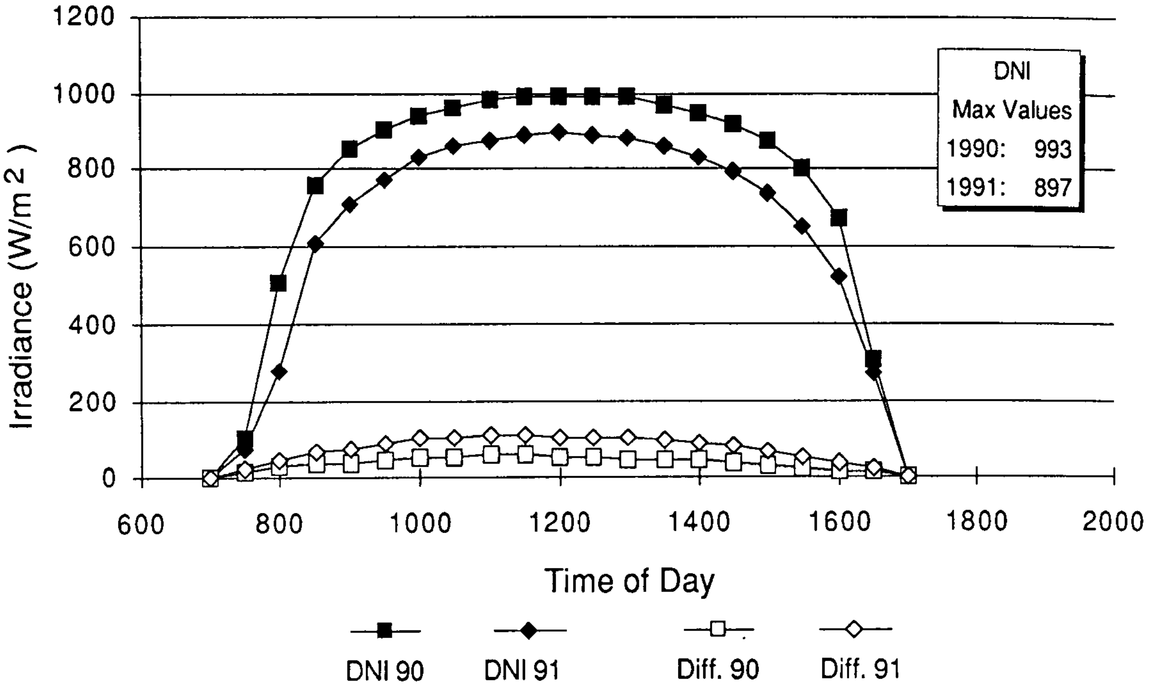

Figure 4-6. Direct Normal and Diffuse Irradiance -- Carrisa Plains, California
12/8/90, 12/4/91.

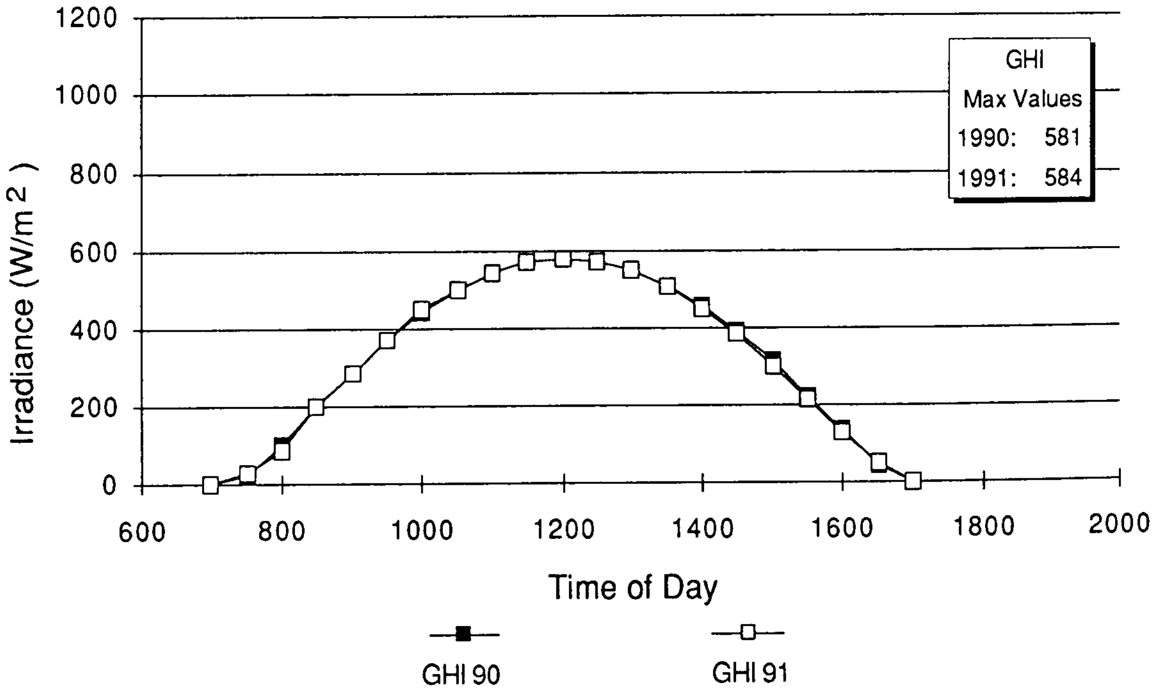

Figure 4-7. Global Horizontal Irradiance -- Carrisa Plains, California
12/8/90, 12/4/91.

5.0 ALBUQUERQUE, NEW MEXICO

Solar resource data have been recorded at the Solar Insolation monitor station at Sandia National Laboratories (SNL) in Albuquerque, New Mexico, since February 1991. The site is west of the Rio Grande, in the foothills of the Sandia Mountains, in the central region of the state. The longitude and latitude of the location are W 106.62° and N 35.05°. The elevation is 1619 meters (5310 feet). On site is an Eppley Normal Incidence Pyrheliometer (NIP) to measure direct normal irradiance, an Eppley Precision Spectral Pyranometer (PSP) to measure global horizontal irradiance, and an Eppley shadow band and PSP to measure horizontal diffuse irradiance.

5.1 Recorded Insolation

Table 5-1 presents the direct normal insolation recorded in Albuquerque for the period of February 1991 through December 1992.

Table 5-1
Direct Normal Insolation for Albuquerque, New Mexico: 1991 - 1992

Month	1991 (kWh/m^2)	1992 (kWh/m^2)
January	-	130.5
February	147.5	109.5
March	169.1	138.9
April	266.7	205.2
May	289.2	150.3
June	246.7	234.5
July	192.6	207.1
August	209.6	218.4
September	180.2	229.2
October	205.7	162.4
November	156.3	136.0
December	110.9	81.2

Table 5-2 presents the global horizontal insolation recorded in Albuquerque during the same period.

Table 5-2

Global Horizontal Insolation for Albuquerque, New Mexico: 1991 - 1992

Month	1991 (kWh/m^2)	1992 (kWh/m^2)
January	–	90.6
February	110.3	106.3
March	151.4	146.0
April	213.3	200.9
May	246.7	196.9
June	226.6	224.4
July	211.5	214.2
August	201.4	206.9
September	164.9	177.9
October	143.7	129.2
November	97.3	92.9
December	78.2	72.1

Figure 5-1 shows the Direct Normal Irradiance (DNI) recorded over the two-year period. Two data points are plotted for each day: the half-hourly average value recorded for the period from 11:30 am to 12:00 pm, and the half-hourly average value recorded for the period from 12:00 pm to 12:30 pm.

As with the data recorded in Las Cruces, the DNI data recorded in Albuquerque show the effects of the Pinatubo eruption. DNI levels recorded during the first half of 1992 were approximately 10% less than those recorded during the first half of 1991. In addition, at no time following the eruption did DNI values reach 1000 W/m^2.

Figure 5-2 shows the Global Horizontal Irradiance (GHI) recorded for the three-year period. Again, the two half-hourly records that bracket solar noon are plotted for each day. In general, the 1992 summer values are slightly lower than those recorded in 1991.

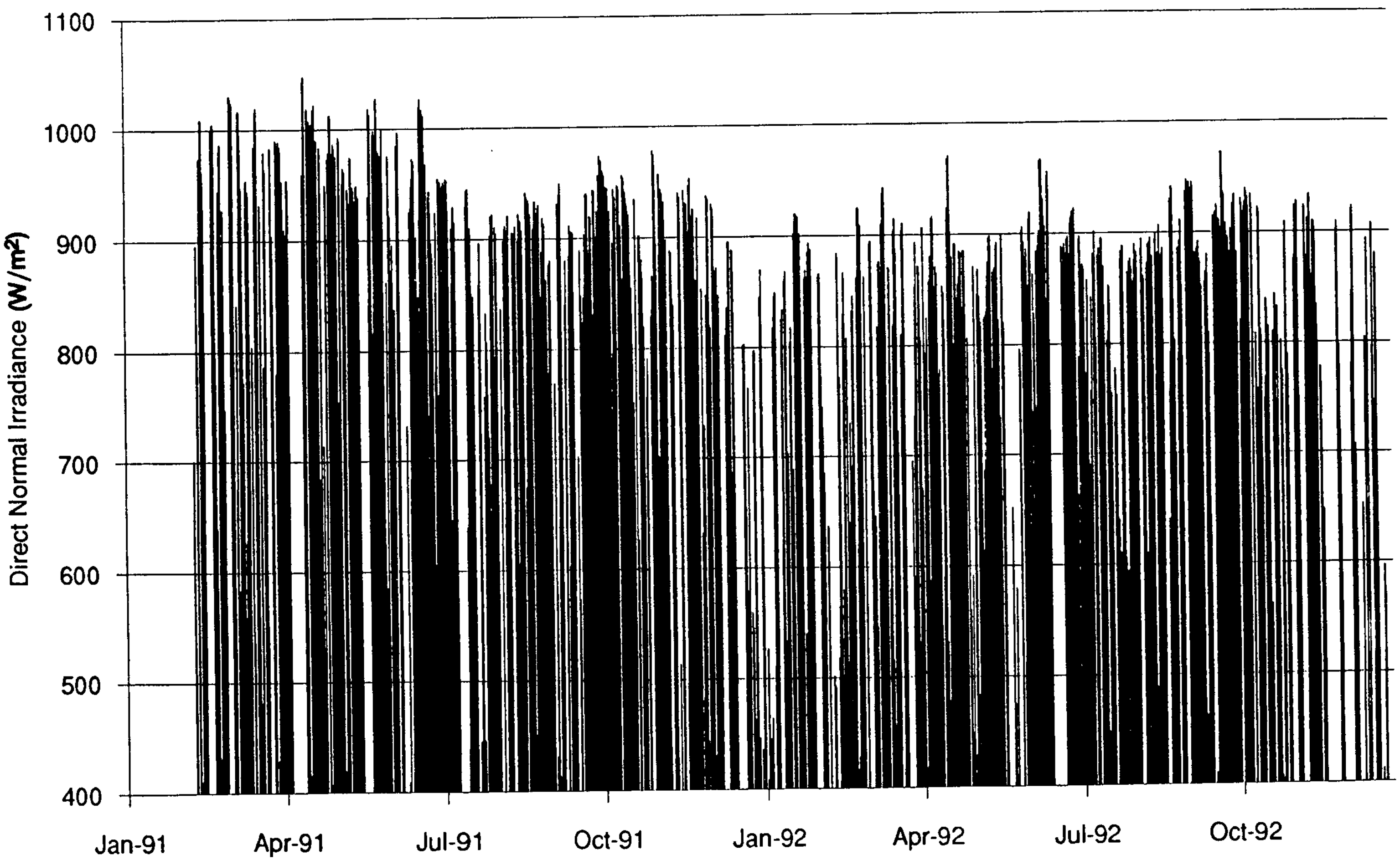

Figure 5-1. Direct Normal Irradiance -- Albuquerque, New Mexico: February 1991 through December 1992.

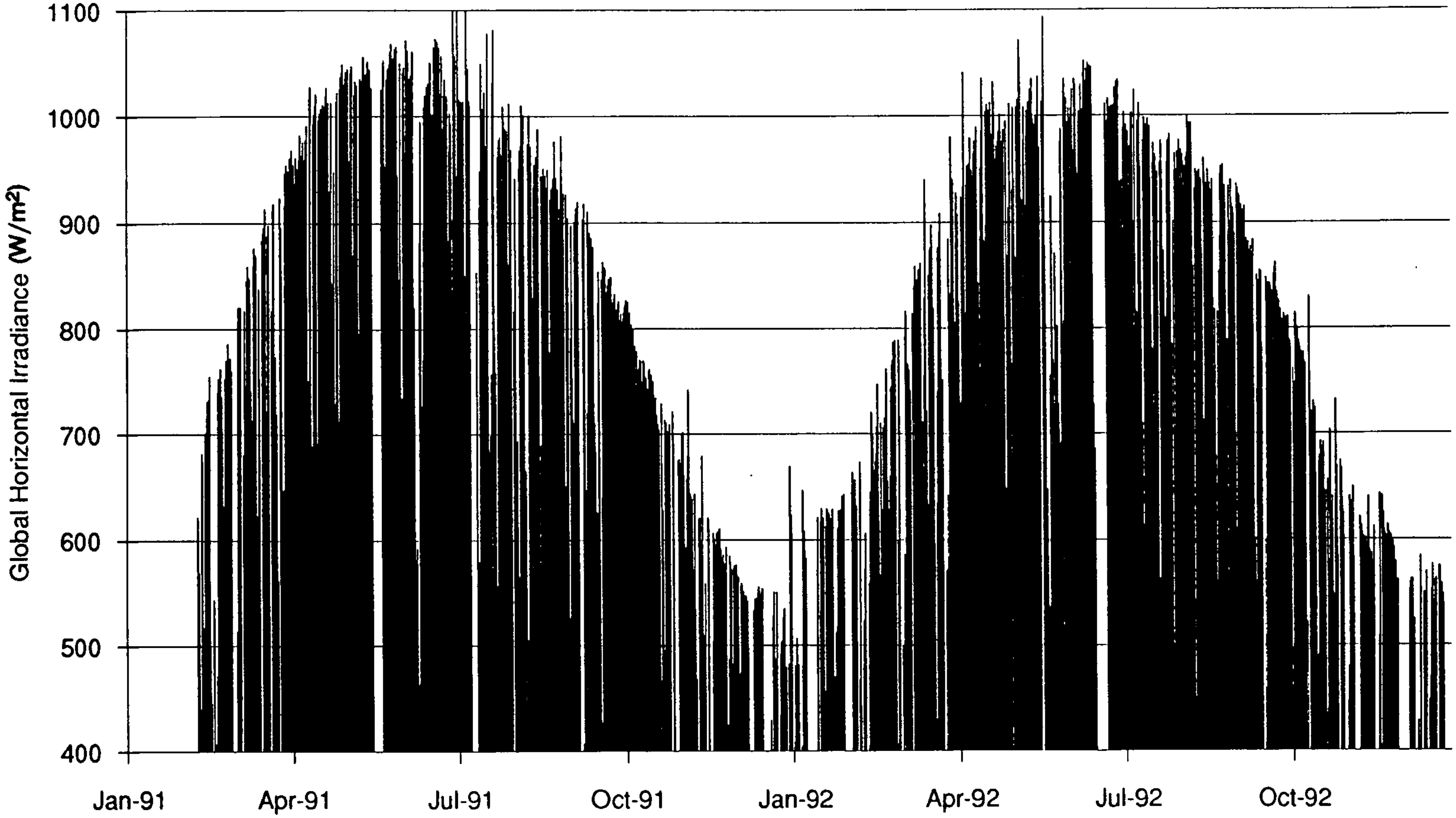

Figure 5-2. Global Horizontal Irradiance -- Albuquerque, New Mexico: February 1991 through December 1992.

5.2 Effects on Direct Normal Irradiance

Figure 5-3 presents a qualitative illustration of the effects of the Pinatubo eruption on DNI levels recorded in Albuquerque, New Mexico. The only pre-eruption data available were for the period of February 1991 through July 1991. Thus, 'clear sky' DNI ratios were generated with data collected from February 1992 through July 1992 (post-eruption period) compared with data from February 1991 through July 1991 (pre-eruption period). As outlined in the previous section, the method used to screen for clear sky conditions extracted, for each day of the year, the single maximum DNI value observed during a 15-day period. That is, for day n, the value used was the maximum DNI observed in the period from day n-7 to day n+7. Quotients were generated by dividing the extracted value for each day of the post-eruption period of 1992 by its corresponding pre-eruption 1991 value. In this way, the 1992 data were indexed against pre-eruption (1991) conditions.

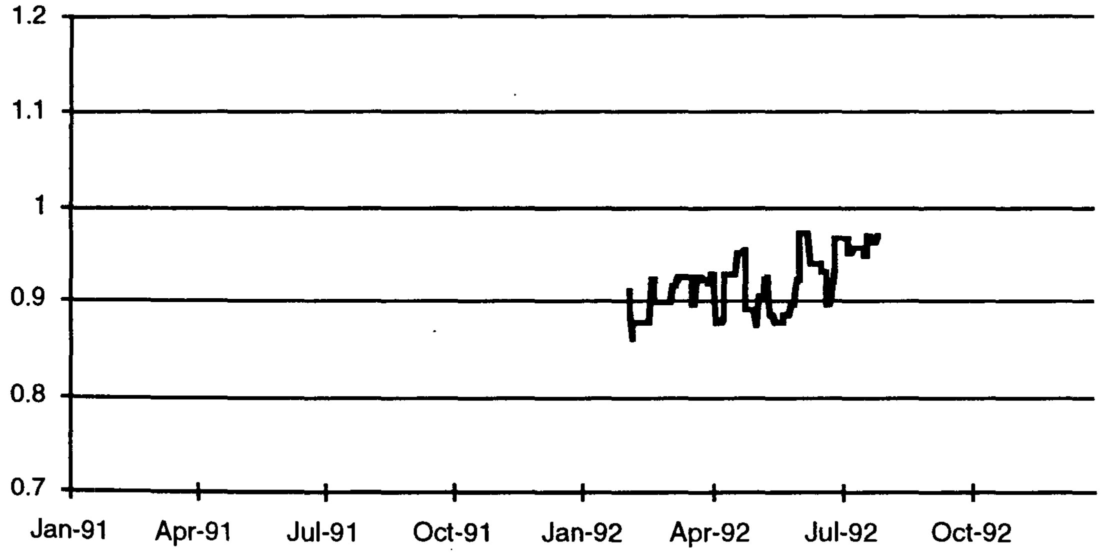

Figure 5-3. Clear Sky DNI Quotients -- Albuquerque, NM 1992/1991.

As described earlier, the effect of the eruption was a reduction of the DNI. In this case, the values recorded during the first quarter of 1992 were approximately 12% below those recorded during the same period in 1991. By summer 1992, the attenuation of the DNI was less pronounced and the ratio of post- to pre-eruption values began to rise.

5.3 Typical Cloudless Days

The data were examined to select days that had been cloudless or near cloudless in each of the two years. Two sets of these days are presented here.

Figure 5-4 shows DNI and diffuse irradiance data recorded on individual days in two consecutive years: March 8, 1991, and March 6, 1992. Figure 5-5 shows the GHI data recorded during these two days.

As shown in Figure 5-4, the 1992 DNI data, recorded nine months after the eruption, show attenuation when compared with the pre-eruption data recorded in early 1991. The DNI values recorded at 12:30 were 1017 and 896 W/m^2 in 1991 and 1992, respectively. Expressed on a percentage basis, the DNI was down 12% in 1992 compared with 1991. The midday 1992 diffuse data show an increase of approximately 45 W/m^2 compared with 1991.

Figure 5-6 shows the DNI and diffuse data recorded on June 16, 1991, and June 14, 1992. Figure 5-7 shows the GHI data recorded during these two days. As observed elsewhere, the effects of the eruption diminished during the summer months. The DNI values recorded at 12:30 were 929 and 932 W/m^2 in 1991 and 1992, respectively.

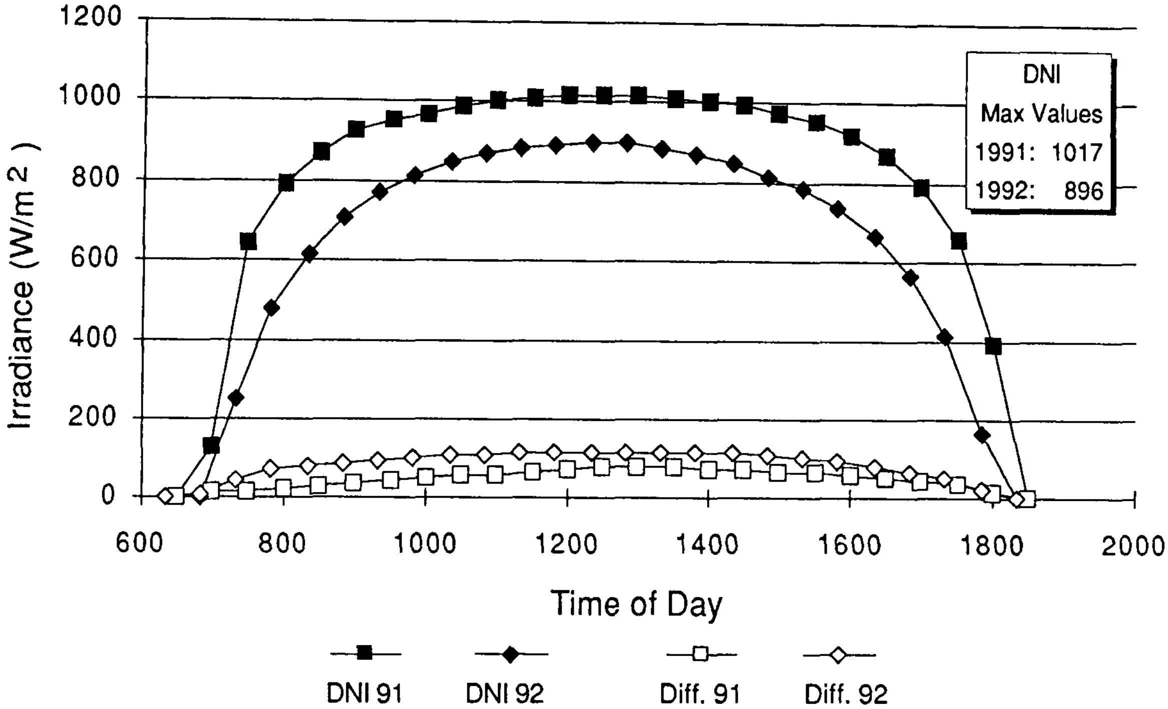

Figure 5-4. Direct Normal and Diffuse Irradiance -- Albuquerque, New Mexico
3/8/91, 3/6/92.

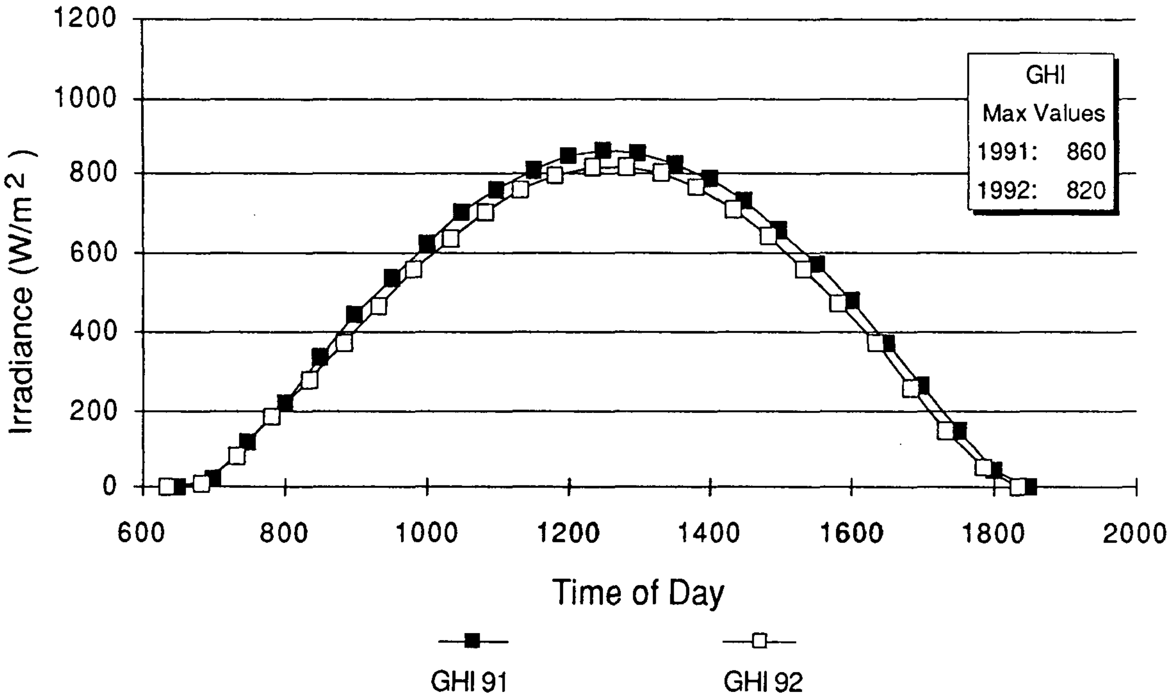

Figure 5-5. Global Horizontal Irradiance -- Albuquerque, New Mexico
3/8/91, 3/6/92.

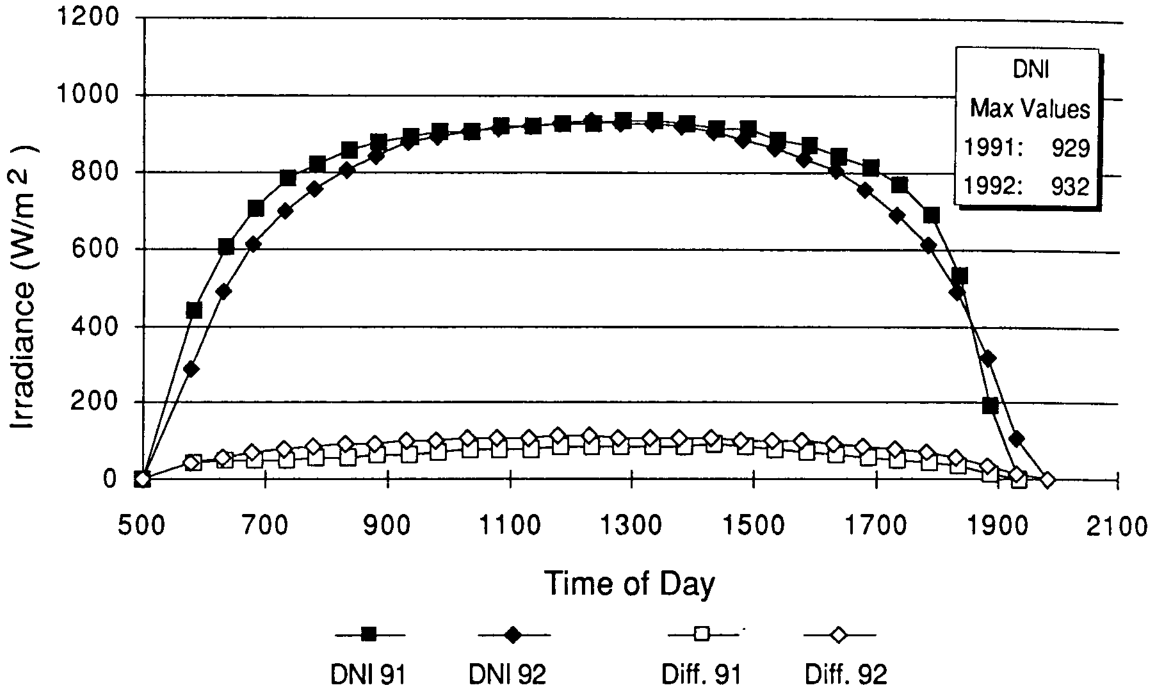

Figure 5-6. Direct Normal and Diffuse Irradiance -- Albuquerque, New Mexico 6/16/91, 6/14/92.

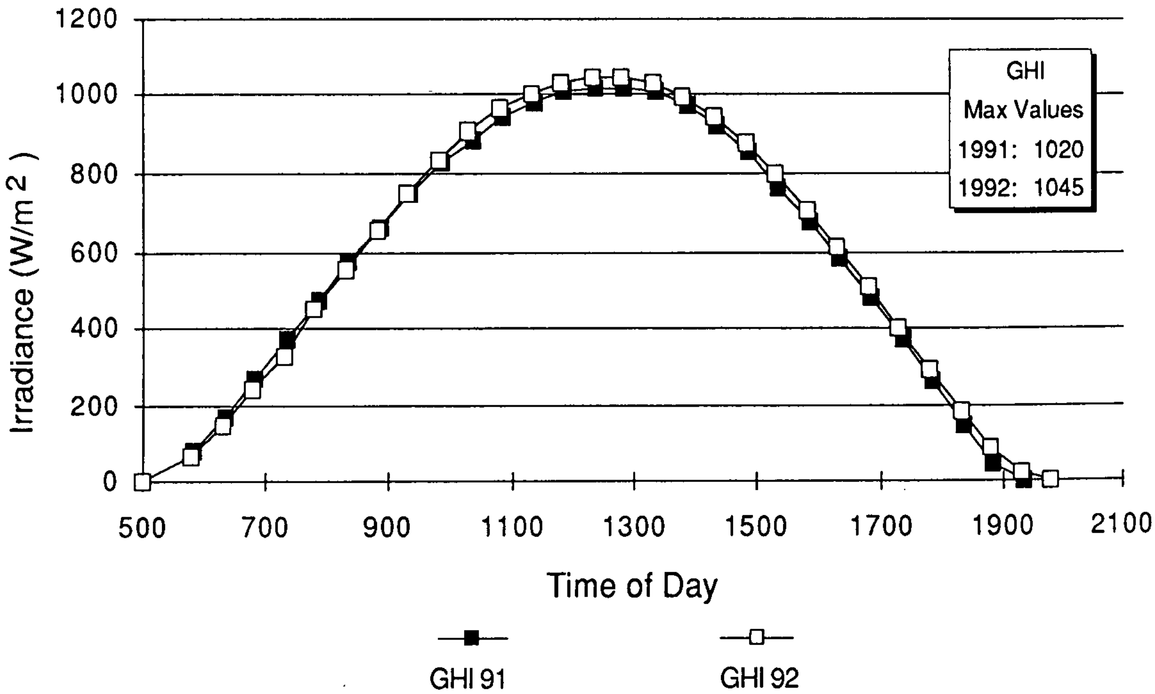

Figure 5-7. Global Horizontal Irradiance -- Albuquerque, New Mexico 6/16/91, 6/14/92.

6.0 DATA QUALITY ASSURANCE

Several steps of quality assurance (QA) checking were applied to all data used in this report. Data fields that failed QA were flagged and the flagged fields were *manually* inspected before any action was taken. Remediation of a flagged field was possible for sites that monitor global horizontal, direct normal, and horizontal diffuse irradiance when only a single field was erroneous per given record. When more than one field per record was flagged, or when less than three solar instruments were in use, the flagged values were examined and discarded.

Throughout all QA processing, the value of 1367 W/m^2 was used for the solar constant. Solar position was calculated according to the method outlined by Iqbal (5).

For each site, the first step of QA was gross range checking of the data. At the low end, all negative values were flagged. To evaluate the upper limit, a clear sky value for transmittance of beam radiation was calculated according to Hottel (6). This model requires the derivation of site-specific coefficients. These were refined via inspection against actual data from each site and ultimately selected to pass all but the most recognizably egregious data. The upper limit of acceptability for DNI was 1.2 times the product of the solar constant times the calculated transmittance coefficient. Horizontal irradiance was compared against this upper limit times the cosine of the sun's zenith angle. For diffuse irradiance, any value was flagged that exceeded 0.9 times the global horizontal irradiance.

At three of the four sites, direct normal, horizontal diffuse, and global horizontal irradiance are monitored. Testing was performed to determine whether the global horizontal irradiance was within 10% of the sum of the diffuse irradiance plus the product of the direct normal irradiance times the cosine of the solar zenith angle. When data from Las Cruces consistently failed this test, it was discovered that the datalogger clock had drifted. Correction of the time stamp associated with the data records was undertaken. This enabled all of the data to pass QA.

Though time consuming, the requirement that all questionable data be manually inspected has proven to be a prudent practice in the preparation of reports of this kind.

7.0 CONCLUSIONS

Analysis of recorded data from four sites in the western United States has revealed some of the effects of the eruption of Mount Pinatubo on solar insolation levels. Conclusions based upon these analyses are:

- Direct normal irradiance has been reduced from historical levels. The attenuation of DNI has followed a cyclical pattern: greatest attenuation during the winter months, less during the summer months. During January 1992, clear sky DNI values were only 80% to 85% of the values recorded in 1990. During the summer of 1992, these values were essentially unchanged from their 1990 levels. By December 1992, clear sky DNI was again attenuated, reaching only 85% to 95% of 1990 levels.

- Greater scattering due to volcanic aerosols increased the level of horizontal diffuse irradiance following the eruption. Increases over historical levels of 100% (50 - 60 W/m^2) were recorded during the first winter months following the eruption.

- The eruption's net effect on global horizontal irradiance has been less pronounced than on the direct and diffuse irradiance components.

SUMMARY

The objectives of this report were to identify and to quantify the effects of the Mount Pinatubo eruption of June 1991 on solar insolation levels. Solar insolation data from four sites in the western United States were obtained for analysis. The four sites studied were:

- The Southwest Region Experiment Station in Las Cruces, New Mexico;
- The Solar Radiation Research Laboratory at the National Renewable Energy Laboratory in Golden, Colorado;
- The Solar Insolation Monitor Program station operated by the Pacific Gas and Electric Company in Carrisa Plains, California;
- The Solar Insolation monitor station at Sandia National Laboratories in Albuquerque, New Mexico.

In general, the findings for all four sites are consistent. At each location, Direct Normal Irradiance (DNI) was reduced following the eruption. The greatest attenuation of the DNI was observed during the winter of 1991/92. At this time, clear sky DNI levels reached only 80% to 90% of the values recorded a year earlier.

At all sites, attenuation due to the eruption abated during the spring and summer of 1992. DNI levels recorded on clear days in the summer of 1992 were similar to those recorded prior to the eruption.

During the latter half of 1992, the second winter following the eruption, attenuated DNI levels were again observed. Clear sky DNI levels for the fall and winter of 1992 were approximately 85% to 95% of the values recorded in 1990.

Diffuse horizontal irradiance levels increased following the eruption. Midday clear sky levels increased 50 - 60 W/m^2 during the winter of 1991/92. The net effect, therefore, on the Global Horizontal Irradiance (GHI) was far less than on the DNI.

To illustrate Pinatubo's effects, plots showing comparisons of 1991 vs. 1990 and 1992 vs. 1990 'clear sky' DNI values were made. The method used to screen for clear sky conditions extracted, for each day of the year, the single maximum DNI value observed during a 15-day period. That is, for day n, the value used was the maximum DNI observed in the period from day n-7 to day n+7. Quotients were generated by dividing the extracted value for each day of 1991 and 1992 by its corresponding 1990 value. In this way, the 1991 and 1992 data were indexed against pre-eruption (1990) conditions. Figure S-1 shows the normalized clear sky DNI ratios obtained for Las Cruces, New Mexico. Figure S-2 shows the same ratios generated for Golden, Colorado.

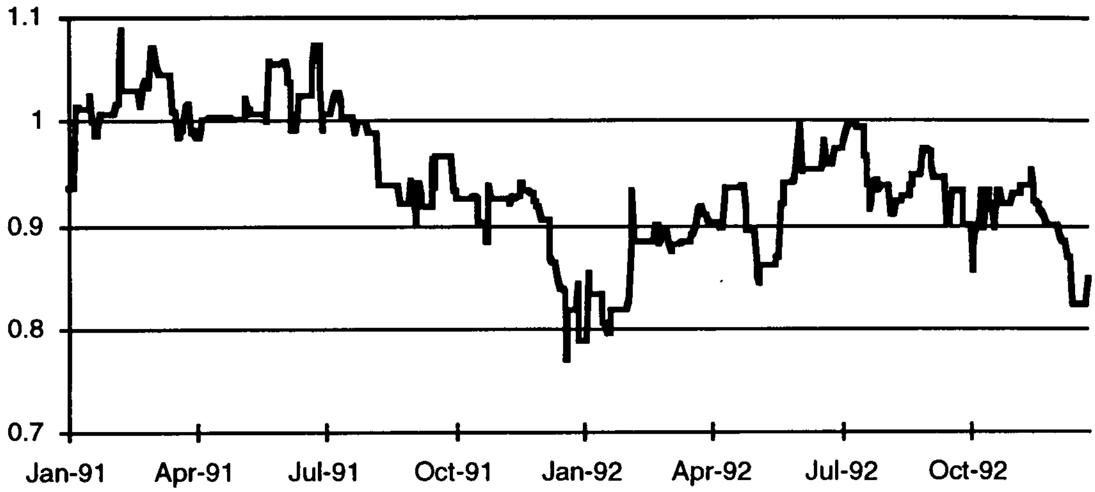

Figure S-1. Clear Sky DNI Quotients -- Las Cruces, NM.

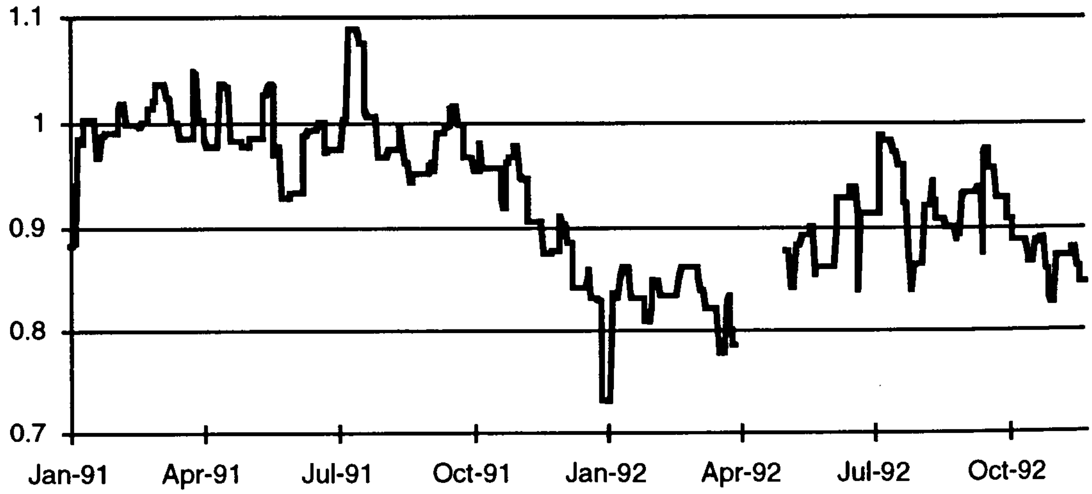

Figure S-2. Clear Sky DNI Quotients -- Golden, CO.

As the figures illustrate, during the first half of 1991 DNI levels at both sites were comparable to those recorded in 1990. The normalized ratios were approximately 1.0 at this time. Following the eruption in June 1991, a cyclic pattern of attenuation was seen: greater attenuation in the winter, less in the summer.

DNI levels at both sites during the winter of 1991/92 were only 80% of their 1990 levels. This was followed by several months of decreasing attenuation. During the summer of 1992, DNI levels were within a few percent of their 1990 values. Attenuation again increased as the latter half of 1992 progressed. DNI levels in December 1992 were well below those of 1990 but were higher than recorded in 1991.

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